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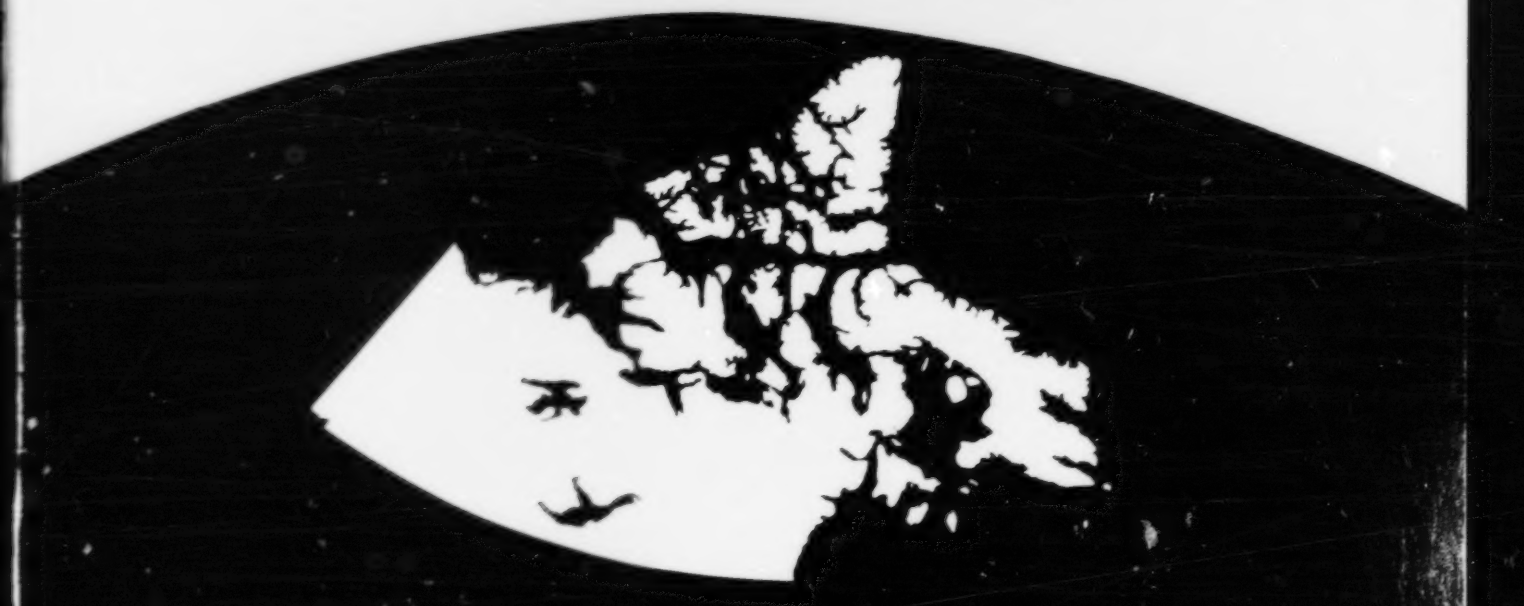
Environmental Studies No 35

Sump Studies V - Ecological Changes Adjacent to Sumps at Exploratory Wellsites in the Mackenzie Delta and Northern Yukon

(A Summary Report)



Canada

Environmental Studies No 35

Sump Studies V - Ecological Changes Adjacent to sumps at Exploratory Wellsites in the Mackenzie Delta and Northern Yukon

(A Summary Report)

Northern Affairs Program

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The views, conclusions and recomendations expressed herein are those of the authors and not necessarily those of the Department.

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RÉSUMÉ

PRÉFACE

Ce rapport vise à rassembler les principaux résultats des enquêtes menées par les auteurs, entre 1977 et 1981, sur les répercussions environnementales de l'élimination des déblais de forage et de leur dispersion dans la partie ouest des terres de l'Arctique canadien. Ces études, subventionnées par les Affaires indiennes et du Nord Canada (AINC), Environnement Canada et l'Association des exploitants de pétrole de l'Arctique, ont été effectuées sous les auspices du Projet de recherches sur l'utilisation des terres de l'Arctique. Le but des enquêtes était de fournir des renseignements permettant d'améliorer les critères de gestion afin de minimiser la dispersion des déblais de forage et la dégradation de l'environnement qui peut en résulter.

Parmi les rapports contenant des détails spécifiques sur les enquêtes soumises à la Division des études environnementales (AINC), il y a :

(i) Ecological changes adjacent to sumps at exploratory wellsites in the Mackenzie Delta, sept. 1984, 114 pp.

(ii) Ecological changes adjacent to sumps at exploratory wellsites in the Northern Yukon, jan. 1985, 88 pp.

Des exemplaires de ces rapports sont disponibles à la bibliothèque des Affaires indiennes et du Nord Canada (Ottawa) et dans les bibliothèques régionales à Yellowknife (T.N.-O.) et à Whitehorse (Yukon). D'autres exemplaires se trouvent à la bibliothèque de l'Artic Institute et à celle du Conseil national de recherches.

Le présent rapport décrit les conditions environnementales de trois chantiers de forage d'exploitation, deux dans le delta du Mackenzie et un au Yukon. Le rapport ne décrit cependant pas en détail les méthodes utilisées dans l'enquête sur ces chantiers de forage et d'autres chantiers. De même, seuls les résultats importants relatifs aux trois chantiers considérérés sont donnés. On peut obtenir des détails spécifiques sur toutes les enquêtes en consultant les rapports susmentionnés.

INTRODUCTION

Dans le nord du Canada, les déblais de forage sont habituellement enfouis dans des bassins à boue souterrains, remplis après le forage et recouverts d'un monticule permettant de compenser la subsidence. Les déblais ainsi emmagasinés gèlent habituellement in situ. Cependant, des problème; peuvent se produire (French 1978a, 1978b) entraînant une détérioration du bassin à boue et des fuites.

D'habitude, les problèmes sont liés au remplissage du bassin à boue (French 1978a) : rupture de la surface gelée de remplissage sous le poids des morts-terrains; subsidence résultant de l'inclusion de matériaux gelés dans les déblais de remplissage; perte de volume du remplissage lorsque les inclusions de glace fondent, créant des masses d'eau qui agissent comme des "puits de chaleur" au-dessus du bassin; fuite de fluides là où des masses de glace exposées dans les parois du bassin fondent; aménagement de bassins à boue dans des endroits sujets à l'érosion et donc aux fuites.

Les autres problèmes liés aux bassins à boue comprennent l'élargissement dû à la fonte des parois (fréquent dans le cas des forages d'été) et l'exposition de masses de glace, ce qui peut entraîner des fuites de fluides par érosion préférentielle. Les perturbations du terrain augmentent bien sûr quand de nouveaux bassins sont creusés.

La détérioration d'un bassin à boue peut causer de graves dommages à la végétation et modifier les propriétés du sol. Strosher (1978) a trouvé que des fluides de bassins à boue riches en KCl (6 300 - 33 000 ppm en sels totaux) entraînaient une réduction de 5 à 30% de la couverture végétale et de 37 à 60% de la productivité. Edwards et Blauel (1975) ont démontré que de fortes concentrations en Na (16 000 à 22 400 mg/L) et en Cl (24 400 à 35 000 mg/L) détruiraient la végétation à court terme et dégraderaient les sols à long terme. Les plantes semblent être endommagées à la fois par contact des tissus avec des sels et par absorption de sels. D'autres éléments présents dans les fluides de bassins à boue (ex. Cd, Cu et Pb) peuvent être phytotoxiques en fortes concentrations; toutefois, sous forme dissoute, les concentrations variant de 0,05 à 0,12 mg/L sont habituellement faibles (Beak 1974, Bryant et al., 1974).

OBJECTIFS

Les buts principaux de cette recherche étaient d'étudier trois chantiers de forage d'exploration dans le delta du Mackenzie : Ogruknang M-31, Siku E-21 et Parsons D-20 et trois emplacements dans le nord du Yukon : Caribou N-25, N. Parkin D-61 et Peel H-71, en vue de : i) recueillir des renseignements sur les changements survenus dans les sols et la végétation en contact avec des déblais de forage enfouis dans des bassins a boue; ii) identifier les agents phytotoxiques des déblais et déterminer leur devenir après la décharge de fluides de forage; et iii) établir une corrélation entre les changements dans la végétation et les perturbations physiques du terrain, les variables abiotiques et topographiques de l'emplacement et particulièrement, dans la mesure du possible, les caractéristiques toxicologiques des fluides de forage. Le but ultime était de fournir des renseignements permettant d'améliorer les critères de gestion afin de minimiser la dispersion des déblais de forage et la contamination des terrains par ceux-ci.

Il faut insister sur le fait que les études ont été conçues et réalisées sous forme d'enquêtes descriptives des chantiers de forage plutôt que d'analyses expérimentales détaillées. On ne disposait d'aucun renseignement sur l'état des emplacements, les sols et la végétation avant les forages, sauf dans le cas de Siku E-21. Pour essayer de résoudre ce problème, on a prodédé à un échantillonnage dans des régions non perturbées, présumées représentatives de l'environnement des chantiers de forage avant les travaux.

Des renseignements de base ont été obtenus à Siku E-21 avant la dispersion contrôlée de fluides de forage, au cours d'une expérience visant à déterminer si l'épandage en surface des déblais de forage est une solution acceptable sur le plan écologique. Toutefois, même à cet emplacement, pour des raisons pratiques, les études ont pris la forme d'une enquête plutôt que celle d'une analyse expérimentale sujette à un plan d'échantillonnage et à une évaluation statistiques rigoureux.

RECOMMANDATIONS

Les recommandations suivantes sont tirées de notre enquête sur les chantiers de forage du delta du Mackenzie et du nord du Yukon et sont basées sur la prémisse qu'il faut confiner les déblais de forage pour empêcher la contamination des terrains de l'Arctique. Les recommandations ne sont pas classées par ordre d'importance. Il est recommandé de :

1. Continuer à utiliser des bassins à boue pour confiner les déblais de forage.

   Les fluides de forage gèlent normallement in situ en un hiver dans le bas Arctique, de sorte que, dans la plupart des cas, les bassins à boue sont un moyen de confinement efficace.

2. Ne pas aménager de bassins à boue sur des terrains élevés, dans des pentes ou immédiatement adjacents à des pentes. Là où c'est possible, les bassins à boue doivent être aménagés dans des dépressions naturelles fermées exigeant un minimum d'excavation et de construction (afin d'en diminuer sensiblement le coût).

   Jusqu'ici, on a aménagé des bassins à boue sur des terrains élevés et en pente ou près de tels terrains, ce qui entraîne, en cas de détérioration du bassin à boue ou d'érosion des matériaux de remplissage contaminés, une perturbation chimique et physique du terrain en contrebas.

3. Choisir l'emplacement des bassins à boue après une inspection minutieuse des lieux pendant la période sans neige. L'inspection devra être faite par la société de forage et l'organisme de réglementation gouvernemental.

   L'inspection précédant le forage fournira les données permettant d'estimer les risques de dispersion accidentelle de déblais et de prendre immédiatement les mesures appropriées en cas de détérioration du bassin à boue.

4. Ne remplir les bassins à boue qu'après que la majorité des fluides a gelé (ex. le temps minimum serait d'un hiver au moins).

   Cette modification du règlement actuel sur l'utilisation des terres est nécessaire car, dans les cas extrêmes, de très fortes teneurs en sels peuvent empêcher les fluides de geler ou les maintenir dans un état de semi-fluides. Dans ces circonstances, il faut attendre que la majorité des fluides gèlent avant de procéder avec soin au remplissage pour éviter une remontée de fluides non gelés. De plus, il ne faut pas utiliser en quantités excessives des matériaux lourds de remplissage.

5. Éviter la construction de nouveaux bassins a boue pendant et après les opérations de forage.

   La construction de bassins à boue peut entraîner des perturbations de terrain excessives, spécialement quand la surface n'est pas gelée. Il peut y avoir aussi contamination chimique lorsque des fluides, des matériaux contaminés, etc., sont transférés dans le bassin auxiliaire. L'organisme de réglementation doit insister pour que la profondeur définitive du forage et donc la taille du bassin à boue nécessaire pour contenir les déblais de forage soient calculées avec précision sans que ne soient enfreints les règlements existants sur l'utilisation des bassins à boue.

6. Envisager l'épandage en surface des déblais de forage dans les régions où la construction d'un bassin à boue perturbera considérablement le terrain, à condition que la teneur en sels dissous des fluides, spécialement le KCl, soit faible.

   Nous recommandons l'épandage en surface des déblais de forage seulement lorsqu'il est garanti que leur teneur en KCl est faible (moins de 10% en poids). Si l'épandage en surface est la méthode utilisée, il faut contrôler la composition chimique des déblais régulièrement pour empêcher la libération de produits chimiques (particulièrement K, Na et Cl) en concentrations phytotoxiques. Les résultats de ces analyses doivent être soumis à l'organisme de réglementation dès que possible. Toute demande de forage sans utilisation d'un bassin à boue doit être accompagnée d'un plan d'éventualités prévoyant des méthodes d'élimination de rechange.

7. Éviter le plus possible le forage en été.

   Le forage en été expose le bassin à boue à des températures au-dessus de zéro pendant plusieurs mois. Il peut en résulter beaucoup de glissements de terrain et une fonte excessive de masses de glace dans les parois du bassin à boue. De plus le terrain peut être endommagé par le mouvement des véhicules dans les zones de toundra dégelées lors des forages d'été.

Des considérations d'ordre pratique et économique peuvent obliger à faire du forage en été. Dans ce cas, les parois des bassins à boue doivent être recouvertes de feuilles de plastique isolantes, pour minimiser la fonte des parois.

8. Prendre des mesures pour remettre les lieux en état en favorisant les processus de restauration naturelle ou artificielle de la couverture végétale.

   En recouvrant les graviers d'une couche égale de matériaux plus fins, on peut accélérer la restauration de la couveture végétale. En semant de l'herbe, particulièrement l'Arctagrostis arundinacea et la Calamagrostis canadensis, on peut aussi stabiliser les surfaces sujettes à l'érosion et améliorer les milieux édaphiques rudes et dénudés, permettant ainsi aux espèces indigènes de repousser plus rapidement. Un programme de plantation a donné de bons résultats à Parsons D-20.

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PREFACE

The objective of this report is to compile important results of surveys completed by the authors during the period 1977 to 1981 on the environmental effects of disposal and spillage of drilling wastes in the mainland western Canadian Arctic. These studies, funded by the Department of Indian and Northern Affairs (DINA), Environment Canada and the Arctic Petroleum Operators Association, were conducted under the auspices of the Arctic Land Use Research Project. The purpose of the surveys was to provide information for enhancement of management criteria to minimize spillage of drilling wastes and associated environmental degradation.

Reports containing specific details of the surveys submitted to the Environmental Studies Division, DINA include the following:

(i) Ecological changes adjacent to sumps at exploratory wellsites in the Mackenzie Delta, Sept. 1984, 114 pp.,

(ii) Ecological changes adjacent to sumps at exploratory wellsites in the Northern Yukon, Jan. 1985, 88 pp.

Copies of these reports are available in the DINA central library at Ottawa and in the regional libraries at Yellowknife, N.W.T. and Whitehorse, Y.T. Additional copies are in the library of the Arctic Institute and the National Research Council library.

The present report contains findings which characterize environmental conditions at two exploratory wellsites in the Mackenzie Delta and one in the Yukon. Methodologies used in the survey of these and other wellsites visited in both locations were more extensive than reported here. Similarly, only key results from the three sites considered are reported. Those who require additional information should study the reports (listed above) which contain specific details of all the surveys.

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The cooperation of Aquitaine of Canada, Ltd. in providing access to the Yukon wellsites is gratefully acknowledged, with special thanks going to T. Beck and W. Sawoton. The authors also wish to acknowledge the assistance provided by the Yukon office of DINA, particularly A. Williamson (Dawson City) and H. Enfield (Whitehorse).

We wish to especially thank Barbara Webb, Neil Howlett, Chris Powter and Nancy Pierce for their able assistance in the field and laboratory.

INTRODUCTION

In northern Canada, drilling wastes are usually contained in below-ground sumps, infilled upon completion of drilling, and "domed-over" to compensate for subsidence. Wastes contained in this way usually freeze *in situ*. However, problems can occur (French 1978a, 1978b), resulting in sump failure and leaks.

Commonly, problems relate to sump infilling (French 1978a) and include: breakage of the frozen fill surface under weight of the overburden; subsidence resulting from inclusion of frozen material in the infill; loss of fill on melting of incorporated ice with creation of "heat sink" water bodies over the sump; leakage of sump fluids through melting of exposed ice bodies in the sump walls; and locating sumps where erosion and resultant fluid release is likely.

Other sump problems include enlargement due to melting of the sump walls (common in summer drilling), and exposure of ice bodies which can lead to fluids escaping by preferential erosion. Terrain disturbance is naturally increased when construction of additional sumps is required.

Severe damage to vegetation and modification of soil properties can occur as a result of sump breakdown. Strosher (1978) found that KCl-rich sump fluids (6,300-33,000 ppm total salts) caused reductions of 5-30% in plant cover and 37-60% in productivity. Edwards and Blauel (1975) showed that high concentrations of Na (16,000-22,400 mg/l) and Cl (24,400-35,000 mg/l) will destroy vegetation in the short term and degrade soils over the longterm. Plant damage appears to be related to both tissue contact and uptake of salts. Other elements in sump fluids; e.g. Cd, Cu and Pb, may be phytotoxic in high concentrations, however, dissolved levels are usually low, ranging from 0.05-0.12 mg/l (Beak 1974, Bryant *et al*. 1974).

OBJECTIVES

General aims of the research were to survey three exploratory wellsites in the Mackenzie Delta; Ogruknang M-31, Siku E-21 and Parsons D-20, and three sites in the northern Yukon; Caribou N-25, N. Parkin D-61 and Peel H-71, to: i) document changes in soil and vegetation on disposal of drilling wastes in sumps; ii) identify causal agents of phytotoxicity in wastes and determine their fate after release of drilling fluids; and iii) correlate vegetation changes to physical disturbance of terrain, abiotic and topographic variables of the site, and particularly to the possible

toxicological characteristics of the drilling fluids. The overall purpose was to provide information for the development of management criteria to minimize spillage and terrain contamination by drilling wastes.

It must be stressed that the studies were designed and completed as descriptive surveys of wellsites rather than detailed experimental analyses. Information on site conditions, soils and vegetation prior to drilling was unavailable for all sites except Siku E-21. An attempt to overcome this shortfall was made by sampling in undisturbed areas believed to be representative of environmental conditions at the wellsites prior to drilling.

Baseline information was obtained at Siku E-21 before controlled spillage of drilling fluids as part of a test to determine whether surface disposal of drilling wastes is an "environmentally acceptable" option. However, even at this site, for logistical reasons, the studies were of a "survey" nature rather than experimental analysis subject to rigorous statistical design and evaluation.

DESCRIPTION OF STUDY LOCATIONS

Mackenzie Delta

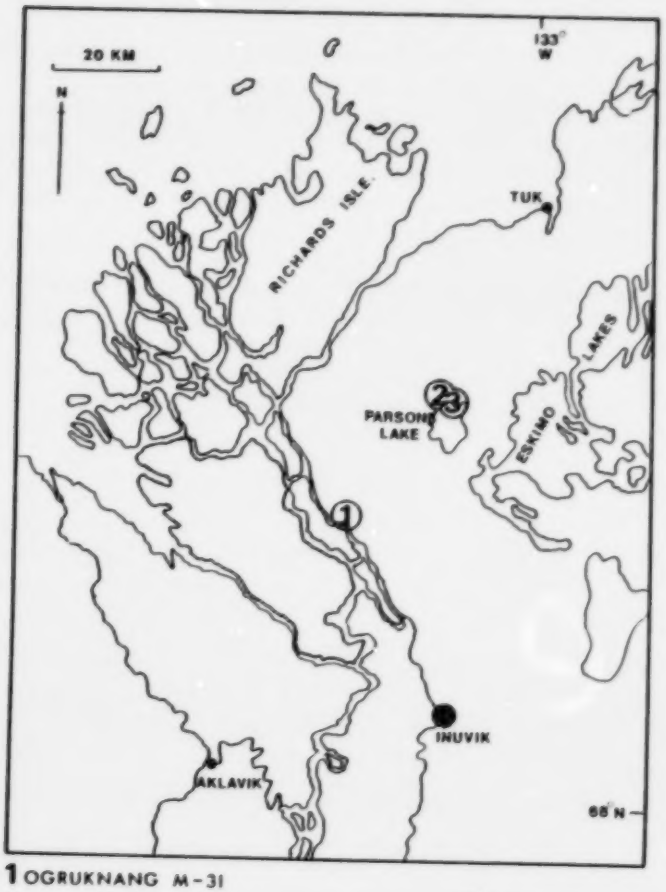
Two Mackenzie Delta wellsites are considered in this report: Siku E-21 (69°00'29N 133°36'54"W) and Parsons D-20 (68°59'N 133°34"W). Both are located close to Parsons Lake in the Pleistocene Mackenzie Delta about 60 km north of Inuvik (Fig. 1).

Elevation in the Parsons Lake area is less than 60 m above sea level except for the occasional pingo. The topography is typically rolling with steepest slopes occurring along the margins of lakes which cover up to 50% of the surface (MacKay 1963). Surface materials consist of fluvial and lacustrine sediments deposited during two glaciations (Fyles 1966). Soils have developed on grey sands and glacial till and normally have an organic layer ranging from a few cm on uplands to 2-3 m depth in raised-centre polygons in lowlands. Mineral soils range from sandy gravels to silt-clays.

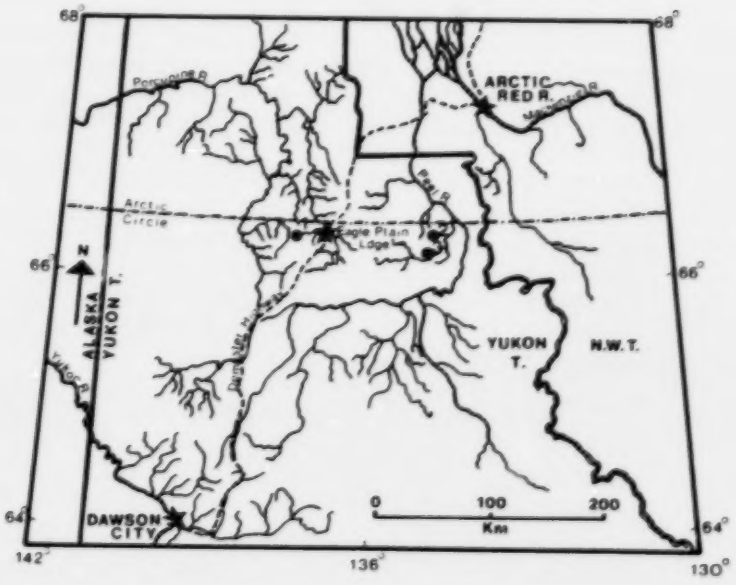
Climate of the Parsons Lake area is influenced by proximity to the Beaufort Sea. Winter temperatures are ameliorated by warmer water underlying the ocean ice pack (Thompson 1967) with February being the coldest month (mean of -30°C). Air temperatures in summer are lowered by the cold ocean and offshore ice, however, above freezing temperatures occur through June to August allowing thawing of the continuous permafrost to depths of 50 cm.

The vegetation at E-21 is characteristic of the Herb-low shrub-heath community (Corns 1974) and at D-20 more closely resembles the medium shrub-heath type. Both communities are dominated by low shrubs such as Betula glandulosa Michx. and a variety of Ericads. Lichen cover is common on the higher topographic locations whereas mosses tend to be confined to the wet organic soils of drainage channels and troughs between hummocks.

Fig. 1 Map of Study Regions.



1 OGRUKNANG M-31
2 SIKU E-21
3 PARSONS D-20



1. Chevron SOBC WH N. Parkin D-61
2. Mobil Gulf Peel H-71
3. Gulf Mobil Caribou N-25

Northern Yukon

Focus of the Yukon section of this report is on Peel H-71 (66°20'N 134°43'W) located on the upland surface of the Peel Plateau at the east edge of the Richardson Mountains (Fig. 1). The Peel Plateau declines in elevation eastwards from about 600 m to 300 m.

Surface materials consist of till deposited by the Wisconsin ice sheet and widely overlain by organic substances. These tills commonly have a clay content in excess of 40% (Zoltai and Pettapiece 1973). Soils in the H-71 area have high ice contents as indicated by hummocks, occasional mudflows and solufluction.

Climate of the Peel Plateau is cold and continental with mean annual air temperatures ranging from -5° to -7°C (Burns 1973). Annual precipitation is about 25 cm.

Vegetation at H-71 mainly consists of open canopy Picea mariana (Mill.) B.S.P. and Picea glauca (Moench.) Voss., along with extensive shrub tundra probably maintained by fire. Ground vegetation is dominated by Ledum spp. and other low-growing shrubs such as Empetrum hermaphroditum L. A moss-lichen layer dominated by Sphagnum and Cladina spp. covers the surface to depths of 10 cm or more.

MATERIALS AND METHODS

Field Sampling:

Siku E-21 was sampled in August 1977 prior to experimental spillage of sump fluids. Sampling was at permanently marked coordinates in an 80 x 80 m grid subdivided into 20 x 20 m blocks with the baseline about 5 m from the downslope sump berm.

Spillage of sump fluids at E-21 was begun in September 1977 with removal of about 5 million litres of supernatant (mostly rainfall) from the sump over a period of five days. Removal of drilling mud was completed in January 1978. A one-metre high berm of mud was constructed downslope of the sump on infilling. Drilling mud was then washed downslope across the sampling grid by meltwater in spring 1978. Chemical composition of the drilling mud was determined from information on additives supplied by Gulf Canada Ltd. and post-spillage sampling of mud deposits. Siku E-21 was resampled in August 1978 (eight months after spillage), and again in August 1980.

Parsons D-20 was sampled in August 1978 and 1980 (after uncontrolled leakage of sump fluids) at marked coordinates in an 80 x 80 grid downslope of the sump. Additional sampling was completed in June 1979 and August 1980 across the edge of a swath of vegetation killed by leaked sump fluids in 1977. This sampling was from two transects at 90° to the swath and located about 137 m and 185 m downslope from the sump. Each transect included a gradient of disturbance ranging from 100% dead vegetation to undisturbed. Chemical composition of the leaked fluids and contaminated soil at D-20 was

supplied by Gulf Canada and the Environmental Protection Service (EPS), Yellowknife, N.W.T.

Peel H-71 was sampled in July 1979 from two parallel 80 m transects downslope of the main sump which extended from the lease into undisturbed vegetation. Additional sampling was completed in August 1980 at coordinates in a 70 x 30 m grid subdivided into 10 x 10 m blocks. The grid was laid out with the edge along the lease and extended into undisturbed vegetation. Composition of leaked fluids at H-71 was determined from information supplied by Gulf Canada, and by the authors for EPS in 1978.

Soils at all grid coordinates and transect sampling points were gathered from pits. Samples of the surface (with plant cover removed) and basal 5 cm of the active layer were removed from the four sides of the pit and made into a composite sample for each soil depth.

Vegetation cover was assessed at sampling points using a one-metre squared quadrat subdivided by crosswires to give 81 points. Percent cover was estimated by vertical projection to the plant canopy at each crosswire and calculating proportion of the quadrat occupied. Estimates included live and dead plants plus bare soil. Vegetation at E-21 and D-20 was also assessed by recording presence/absence of plant species and bare soil in a cluster of four contiguous 50 x 50 cm quadrats at each grid coordinate.

Soil and Vegetation Analysis

Soil samples were analyzed for 1N ammonium acetate-extractable K, Na and Ba after oven-drying at 50°C and sieving through a 20-mesh screen. Zinc and Cu were extracted with a pH 1.0 nitric acid solution using the method of Bryant *et al*. (1976). Chloride was extracted in water.

Cation concentrations in the various extracts and in samples of drilling wastes discharged to sumps at H-71 were measured by atomic absorption spectrophotometry using standard techniques. Chloride was measured by the thiocyanate method using an autoanalyzer (Technicon Instruments Corp. 1976).

Total live vegetation cover at sampling points was expressed as a percentage of the highest recorded total cover at any single point in a particular sampling unit (grid or transect) to give an index of relative species cover (RSCI). RSCI profiles (transects) and distribution maps (grids) were then constructed using computer graphing and mapping techniques.

Where species presence/absence was measured a species richness index (SRI) was derived by expressing the sum of observed occurrences of all species in a quadrat as a percentage of the maximum possible number of occurrences. SRI was calculated for each 20 m interval downslope of the sumps. The SRI data at grid coordinates were also expressed as a percentage of the highest recorded SRI value at each particular site and sampling date to give an index of relative species richness (RSRI). These data were used to draw RSRI maps. A cover index (SCI) was calculated for each sampling point along both transects at D-20 by expressing live cover as a percentage of the total (live and dead) and these values were plotted. Relationships

between live cover of plants on the transects and concentrations of K, Na and Cl in surface soil were assessed by regression analysis.

RESULTS AND DISCUSSION

Site Descriptions and Histories:

Parsons D-20 was drilled between April and December 1976 to a depth of 4,130 m. Amounts of solids used in the drilling (524,387 kg) were high for an exploratory well of this depth and the drilling fluid was particularly rich in KCl (46% by weight of total solids). Waste drilling fluid was discharged to a 14,103 cu. m. capacity sump excavated in fluvio-glacial sands and gravel with a high ice content at the top of a S.W.-facing slope draining towards Parsons Lake (Fig. 2). Infill material was derived from the original excavation and the sump was capped with gravel.

Waste leakage problems developed at D-20 in the summer of 1977 with a seepage of fluids from the S.W. corner of the sump. Ultimately a swath of vegetation was killed which extended 210 m to Parsons Lake (Fig. 2). Soils contaminated by this leak contained high levels of K and Cl (Table 1), suggesting that KCl was the primary cause of plant mortality.

Fluids in the sump remained unfrozen during the winter of 1977-78 as indicated by growth of an icing mound over the original seepage site and borehole tests. Lack of freezing was attributed to hydrostatic pressure exerted by the gravel fill (French 1978a) coupled with high salinity of the waste fluids (EPS Yellowknife Memo, March 13, 1978). Analysis of sump fluids revealed high levels of Ca, K, Na and Cl and low concentrations of heavy metals (Table 2).

A supplementary sump (27,300-31,850 l capacity) was constructed and fluids plus contaminated soil from the original sump and icing mound transferred to it in late March 1978. Waste drilling fluids and contaminated ice were mixed with surrounding soil during this transfer. Melted ice in these materials plus dissolved salts subsequently resulted in the formation of two saline pools (ca. 9 m from the S.E. corner of the original sump) the contents of which moved downslope. By autumn 1978, fluid affected areas, defined by damage to plants, included all upslope areas below the original sump and channels leading to Parsons Lake (Fig. 2).

Vegetation in the fluid-affected areas began to recover in 1980. By August, extensive recolonization by Calamagrostis canadensis (Michx.) Beauv. and Arctagrostis arundinacea (Trin.) Beal. had occurred in a large area of hummocky terrain west of the 1977 swath and along the edges of leakage channels. Other recolonizers were Petasites frigidus L. Fries and Rubus chamaemorus L. However, there were few signs of recolonization in the centres of the main 1977 and 1978 channels. Neither were there any extensions of spill effects into areas previously unaffected.

Fig. 2 Map of Parsons D-20 in 1980 showing areas of sump fluid leakage (not to scale).

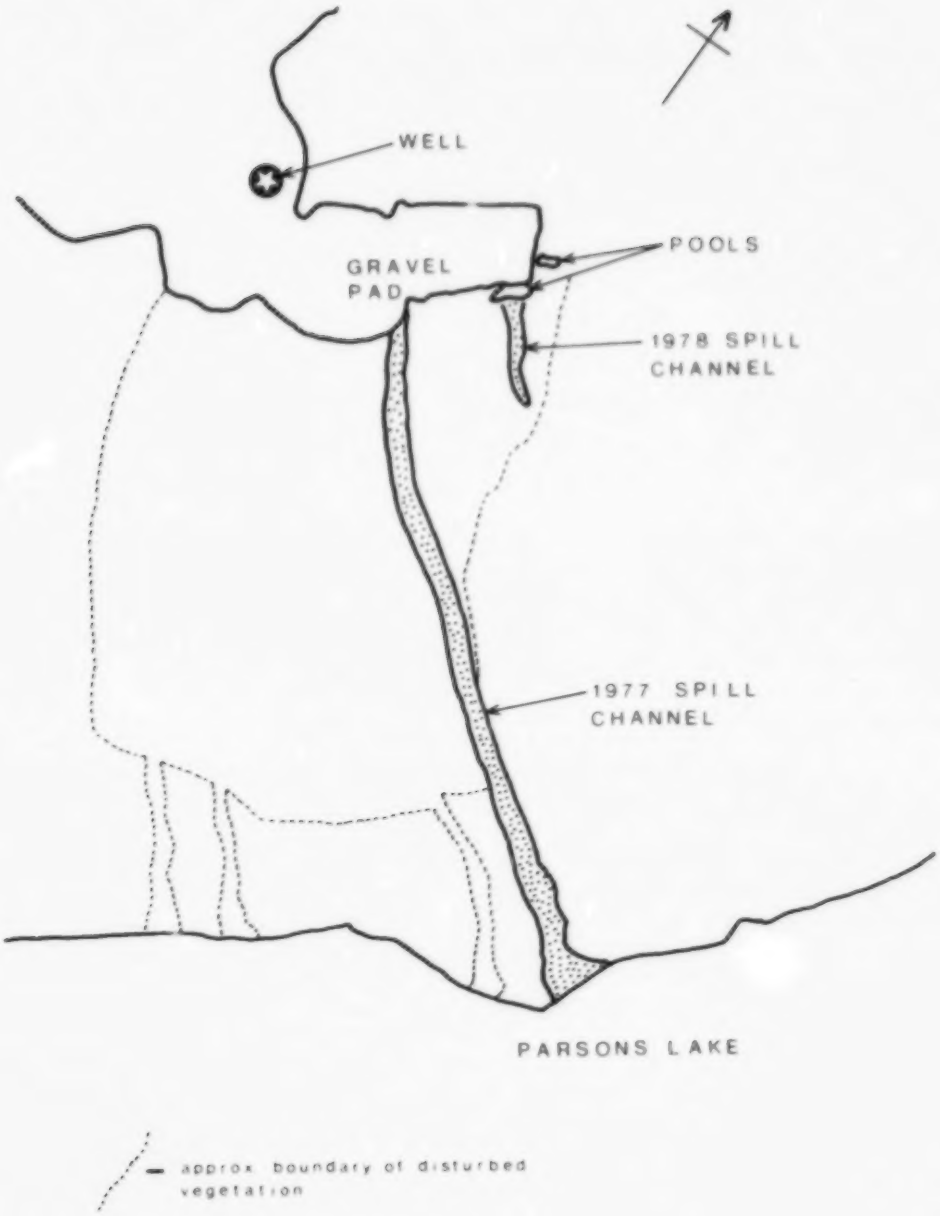


Table 1. Chemical characteristics of soil contaminated by sump fluid seepage at Parsons D-20, sampled August 24, 1977.

	Peat moss approx. 15 cm from surface	Peat moss approx. 45 cm from surface at frost-table
EXTRACTABLE ELEMENTS (mg/kg)		
K	13,780	5,780
Fe	1,770	4,740
Cl	19,600	20,300
TOTAL METALS (mg/kg)		
Zn	27.7	20.4
Cu	4.4	5.4
Pb	<2.5	<2.5
Cr	3.1	34.0
Cd	0.6	0.4
As	<0.3	<0.3

Distance of samples from sump and extraction techniques not specified.

Data from communication between EPS, Environment Canada, Yellowknife, NWT and Gulf Oil Canada Ltd., Inuvik, NWT dated March 1, 1978.

Table 2. Temperature, specific conductivity and total metals, chloride and sulphate content of sump fluids at Parsons D-20 sampled on March 18, 1978.

	Sump			Adjacent to mound		Ice mound
	1	2	3	1	2	
SAMPLE DEPTH (m)	3.96	6.10	4.88	2.13	1.52	
TEMPERATURE (C)	-3.4	-3.1	-2.2	-5.6	-5.5	
SPECIFIC CONDUCTIVITY	60000			100000	90000	
ION CONTENT (mg/kg)						
K	23000	20500	4650	42500	39500	650
Na	4500	3500	700	6250	7000	150
Ca	1850	1800	250	3050	3150	65
Zn	0.4	1.2	1.1	0.7	1.5	0.3
Cu	0.2	0.2	0.3	0.3	0.5	trace
Pb	1.1	1.4	0.5	1.8	1.8	trace
Ni	0.6	0.6	0.4	0.9	1.2	0.1
Cd	0.1	0.1	trace	0.2	0.2	trace
Cr	0.2	0.2	0.2	0.2	0.3	0.2
Fe	45	105	310	205	450	110
Chloride	32900			53400	53400	
Sulphate	16.0			33.0	32.0	

trace -- <0.1 mg/kg

All metals were analyzed by direct aspiration on an AA spectrophotometer.

Data from EPS, Environment Canada, Yellowkife, NWT in memoranda dated March 22 and April 12, 1978.

Siku E-21 was drilled between April and June 1977 to a depth of 3,427 m. Amounts of solids used in the drilling (182,842 kg) were average for an exploratory well of this depth. The mud system was low in KCl (1.3% by weight of total solids) compared to other Low Arctic wells and rich in barites (36% by weight). Waste drilling fluid was discharged to a 11,607 cu. m. sump excavated in fluvio-glacial sands and gravels on a narrow ridge-top which sloped (angles of $+6^{\circ}$) to the level sampling area along the north edge of the lease. Infill material was derived from the original excavation and the sump was capped with gravel. There was no history of sump problems at E-21 and, prior to experimental removal of waste fluids from the sump in September 1977, the sampling area was undisturbed.

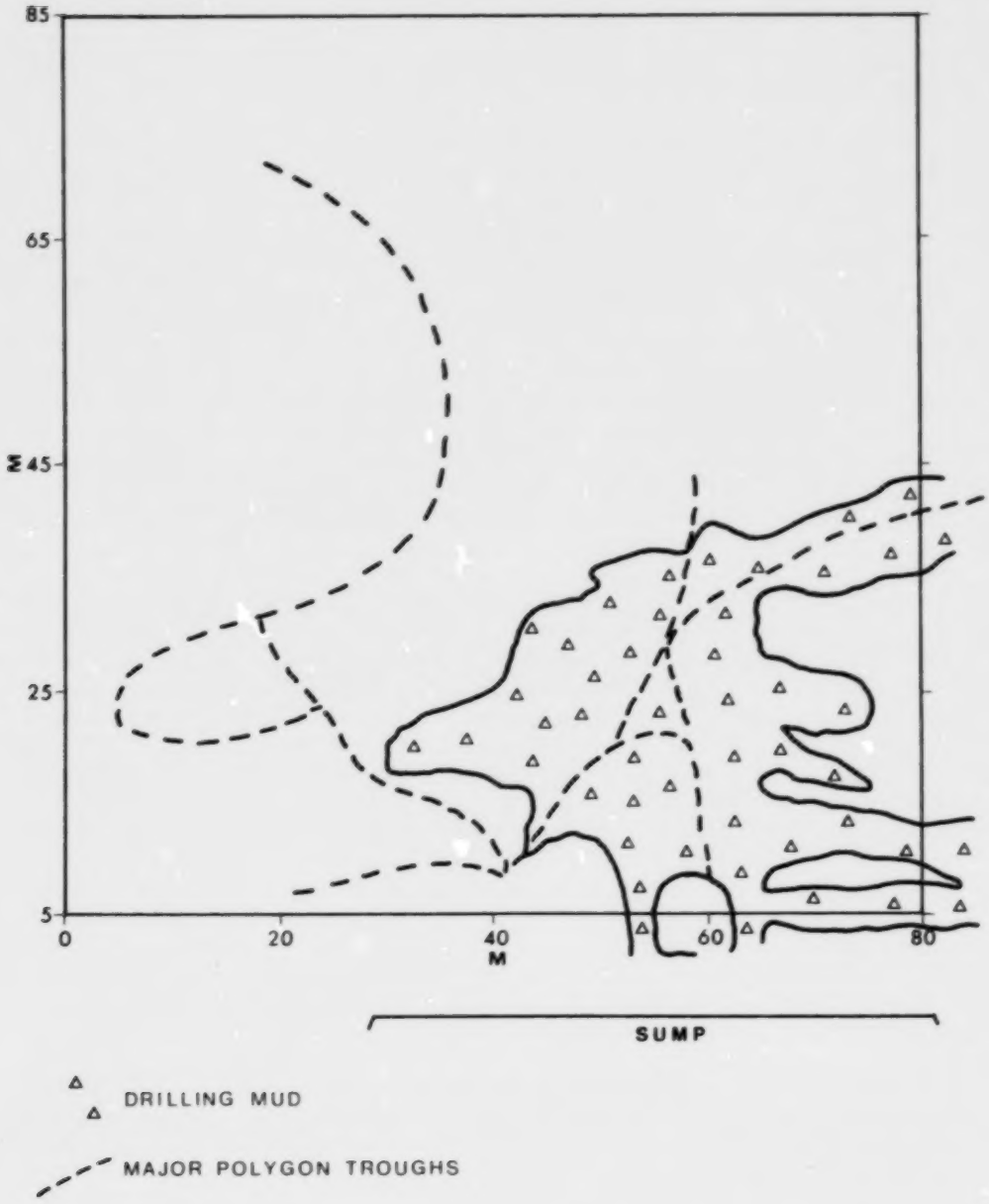
Pumping of supernatant fluids (necessary in order to reach the drilling solids) reduced the depth in the sump by 1.83 m over a 2,773 square metre area. This large volume was distributed across the sampling area but, because of the raised polygon topography, much of the fluid was channelled into the inter-polygon troughs. Serious terrain degradation developed as the ground became waterlogged and the supernatant melted ground ice under the vegetation cover. Two-metre deep channels were created along polygon troughs in three places, other troughs were enlarged, and several small pools 0.2-0.6 m deep were created. Erosion continued until the ground surface collapsed over exposed ice lenses and wedges thus insulating them from further thaw. By August 1980, terrain degradation had ceased and the raised polygons appeared stable. Plant damage from the supernatant spill was confined to the small areas (ca. 5-10% of the sampling area) where vegetation had collapsed into polygon troughs. None of these coincided with the permanent sampling points.

Erosion of the mud berm (constructed in January 1978) by spring meltwater resulted in extensive mud distribution on the surface in the S.W. quarter of the sampling area (Fig. 3). Mud depth was greatest (21-32 cm) between 5 m and 20 m from the sump. Only a thin veneer of mud (2-5 cm deep) covered the surface at 40 m downslope, except in polygon cracks where channeled meltwaters had deposited a thicker (5-15 cm) layer. In general, the mud was dry at the surface, friable, and extensively fractured by shrinkage cracks. Wet mud was only present in the zone of thickest deposits. No further downslope movement of mud was evident in August 1980.

Plant cover in 1978 was reduced by up to 100% compared to the pre-spill condition in all areas of mud deposit. Plant death appeared to be a result of physical burial and there was no visual evidence of toxic chemical effects such as leaf shedding, partial necrosis and chlorosis. Vegetation immediately adjacent to the mud spill was undisturbed indicating that lateral movement of toxic leachates had not occurred.

Revegetation of mud-buried areas began in summer 1978 but cover regeneration was slight (5% or less). By August 1980, regeneration was greater with up to 60% cover restoration on areas of shallow mud deposit. The major colonizers were dominants in the undisturbed vegetation and included Carex spp., Ledum decumbens (Ait.) Lodd., Rubus chamaemorus, Betula glandulosa Michx. and Vaccinium Vitis-idaea L. All were regenerating through shrinkage cracks in the mud from buried vegetative structures present before spillage. Mud burial killed the lichens and there was no evidence of lichen regeneration in 1980. Moss cover was also eliminated initially but by summer 1978 some mosses had regenerated through shrinkage

Fig. 3 Distribution of surface drilling mud following experimental sump fluid spillage at Siku E-21.



cracks and one species, Aulacomnium turgidum (Wahlenb.) Schwaegr., was growing on the drilling mud itself.

All of the regenerating higher plants suffered from premature senescence in August 1978. This effect was most marked with Rubus chamaemorus and may have been caused by relatively high concentrations of chemicals in the mud deposit during the first months after spillage. Premature senescence was not observed in August 1980.

Peel H-71 was drilled between summer 1977 and spring 1978. The mud system contained 18% KCl by weight of total solids, Na-containing compounds amounted to 3.6% and barite additions to 58%. Analyses of the sump contents showed relatively high levels of dissolved K, Na and Cl (Table 3) but concentrations of these elements were up to one magnitude lower than in the salt-rich fluid at D-20. Levels of other dissolved elements in the main sump at H-71 were low (Table 3).

Waste drilling fluids were initially discharged to a 2,035 cu. m. capacity sump constructed in ice-rich silty-clays at the top of a slope. Later a second, auxiliary sump was constructed downslope (Fig. 4) to contain excess fluids (drilling fluids were also used to make a hard ice surface runway on a Hercules airstrip one mile W. of the wellsite).

In July 1979 both sumps showed signs of poor infilling. Escape of toxic wastes had occurred through melt-out of ice in a small retaining dyke at the downslope end of the auxiliary sump. These fluids flowed 150 m along a drainage channel parallel and adjacent to the N.E. edge of the lease. Subsidence on the auxiliary sump over the leakage site led to creation of a surface pool by 1979 but no erosion of fill was evident. Additional slumping with creation of numerous surface pools around the edges of both sumps was apparent in 1980 but there was no evidence of major thermokarst development.

Toxic effects of fluid spillage were apparent in the drainage channel extending from the auxiliary sump as indicated by a narrow (ca. 20 m) swath of dead or dying Picea mariana. Destruction of vegetation on the remainder of the lease mainly resulted from forest clearance, sump construction-infilling, and movement of heavy equipment.

Effects of Sump Fluids on Soils:

Extractable cation levels reflect loading of the soil exchange capacity and are a measure of the ions available to plants. Analyses of ammonium acetate extracts indicated significant soil contamination by K and Na originating in sump fluids. Water soluble chloride was also a major pollutant at all three wellsites. In contrast, acetate-extractable Ba (2-131/kg)* and Fe (1-368 mg/kg) occurred at background levels (soil concentrations in undisturbed areas). Concentrations of the weak-acid extractable heavy metals, Zn (<0.1-200 mg/kg), Cu (<0.1-14 mg/kg) and Pb

*Range across the three wellsites at 0-5 cm soil depth.

Fig. 4 Diagram of Peel H-71 wellsite (not to scale).

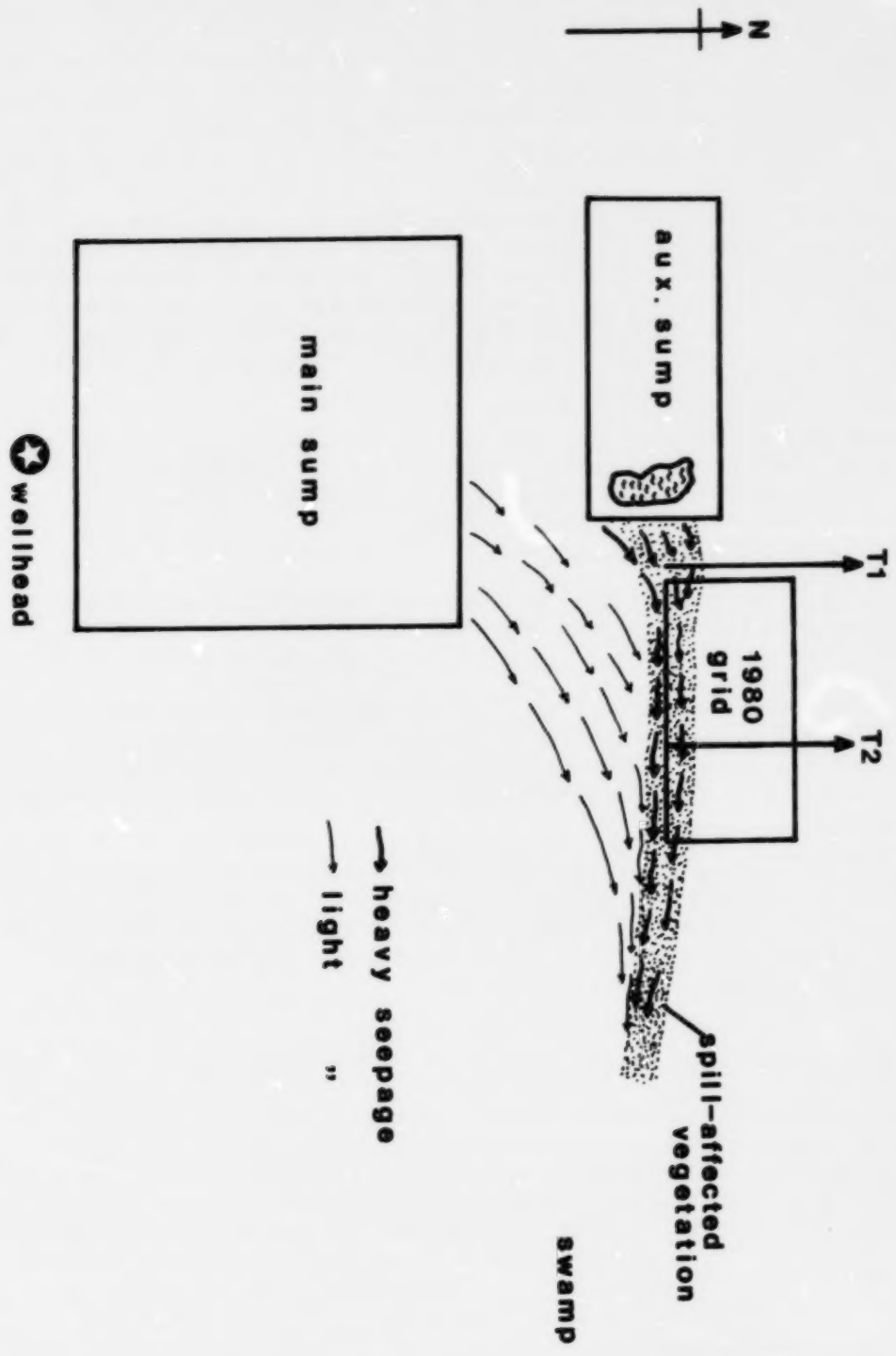


Table 3. Specific conductivity, pH, dissolved metals, chloride, sulphate and bicarbonate content of sump fluids at Peel H-71 sampled on October 23, 1977 (1) and December 20, 1977 (2).

	Main Sump[1]	Sampling Depth (m)[2]	
		0.3-0.6	0.9-1.2
Specific conductivity	19608	---	---
pH	7.9	---	---
Ion content (mg/l)			
K	4344	---	---
Na	1024	1179	1141
Ca	284	---	---
Mg	52	---	---
Zn	---	0.07	0.07
Cu	---	0.05	0.08
Pb	---	0.50	0.58
Cr	---	0.51	0.51
Mn	---	1.64	1.66
Cd	---	0.05	0.04
Fe	---	0.40	0.41
Chloride	5028	---	---
Sulphite	907	---	---
Bicarbonate	825	---	---
	Auxiliary Sump		
Na		1510	1505
Zn		0.07	0.09
Cu		0.08	0.10
Pb		0.57	0.64
Cr		0.23	0.21
Mn		0.58	0.59
Cd		0.05	0.05
Fe		0.48	0.55
Ba		0.26	0.39

1. Analyses completed by Chemical and Geological Laboratories Ltd. for Mobil Oil Canada Ltd.

2. Analyses completed by the authors for the Department of Indian and Northern Affairs, Whitehorse, YT.

(<0.1-0.2 mg/kg) were similarly close to background levels.

Soil contamination by K, Na and Cl from sump fluids ranged in severity between the wellsites. Enrichment of soil by these elements was locally moderate at Siku E-21 and Peel H-71, and both severe and widespread at Parsons D-20. Potassium was present with chloride as KCl in drilling fluids, and in association with iodine as KI at E-21. Na additives to the fluids were mainly sodium bicarbonate and sodium hydroxide.

Enrichment of soils by K from spilled mud solids at E-21 was meager with mean concentrations in the mud and underlying soil of 1,120-1920 mg/kg (cf. 1977 and 1978 distribution maps, Fig. 5). In part this reflected the low initial potassium loading of the drilling fluid in which KCl and KI only accounted for 3% by weight of solid additives. Sump fluids contained more K at H-71 (18% by weight of solid additives) but soil levels were similarly low (1,000-2,000 mg/kg), with elevated concentrations occurring only in the area of fluid leakage west of the auxiliary sump and from 0-20 m from the lease edge (Figs. 6-7). Containment of the bulk of the waste fluids was mainly responsible for the low soil K levels at H-71. However, at both E-21 and H-71, fixation of K in non-extractable form through preferential attachment of K ions to the clay component of the drilling solids (Page and Baver 1939; Ranney 1979) and rapid adsorption of K by soils (Kelley 1948) probably contributed to the low soil concentrations.

Contamination of soils by K from leaked sump fluids at D-20 was more marked. Dissociation of the large amounts of KCl added to the mud mixture at this site evidently freed a large quantity of ionic K which saturated the exchange sites on the mud solids; the excess passed into solution in the supernatant. Eventual release of this unfrozen supernatant resulted in severe soil contamination by K downslope of the sump. Ion exchange sites were initially saturated with K on contact with the supernatant as evidenced by the very high exchangeable levels (up to 28,000 mg/kg in the 1977 spill, Fig. 8; and 50,000 mg/kg in the 1978 spill, Fig. 9) and obvious downslope movement of this ion in soluble form. However, later fixation and adsorption of K may have been partly responsible for the decline in soil levels in spill-affected areas between 1977 and 1980.

Sodium-containing compounds were not major constituents of the mud systems, accounting for about 2.2%, 2% and 4% at E-21, D-20 and H-71 respectively. However, some release of Na from drilling wastes was evident at all three wellsites. Na is one of the least important cations on exchange sites in uncontaminated soil (Chapman 1973), but after contact with Na-enriched sump fluids the proportion of Na on these sites rises sharply relative to Ca and Mg as the latter are precipitated (Edwards and Blauel 1975). Significant ($P_{0.05}$) increases in soil Na downslope of the sumps were indicative of this process. Exchangeable Na at solenetzic concentrations (3-10 me./100 g, Biosystems 1974) occurred in contaminated areas at all three wellsites.

At H-71 movement of Na-enriched sump fluids resulted in soil contamination in the drainage channel paralleling the lease (Figs. 6-7). Soil concentrations were not great (about 1,250 mg/kg), however. Post-spillage concentrations of soil Na at E-21 were higher (about 500-3,400 mg/kg). Elevated Na levels occurred over approximately 35% of the sample grid (Fig. 10) and were mainly confined to the drilling mud deposited on the

Fig. 5 Distribution maps of extractable K in surface soil (0-5 cm depth) at Siku E-21, August 1977, 1978 and 1980.

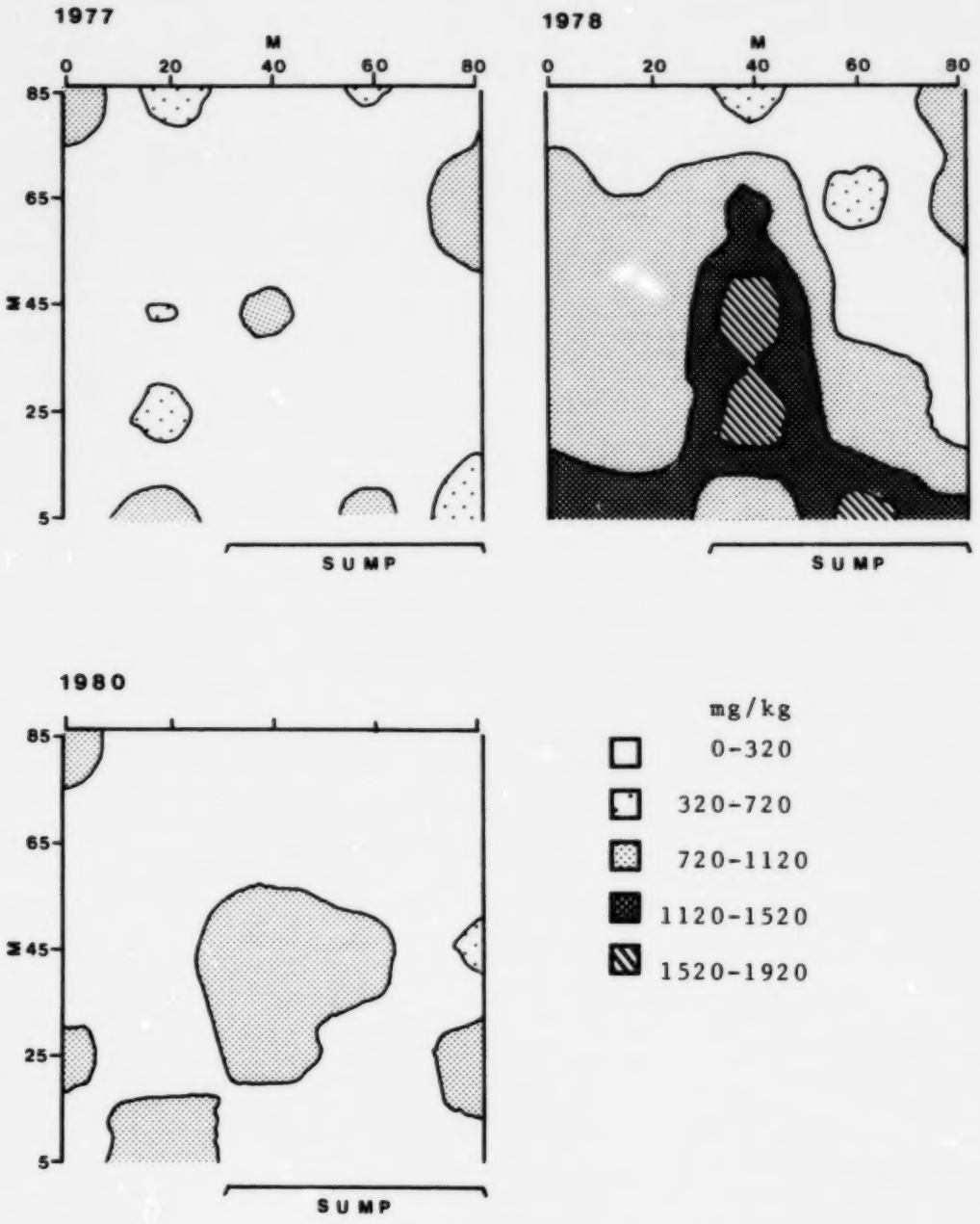


Fig. 6 Concentrations of extractable K, Na and Cl in surface soil on transects T1 and T2 at the Peel H-71 wellsite, July 1979.

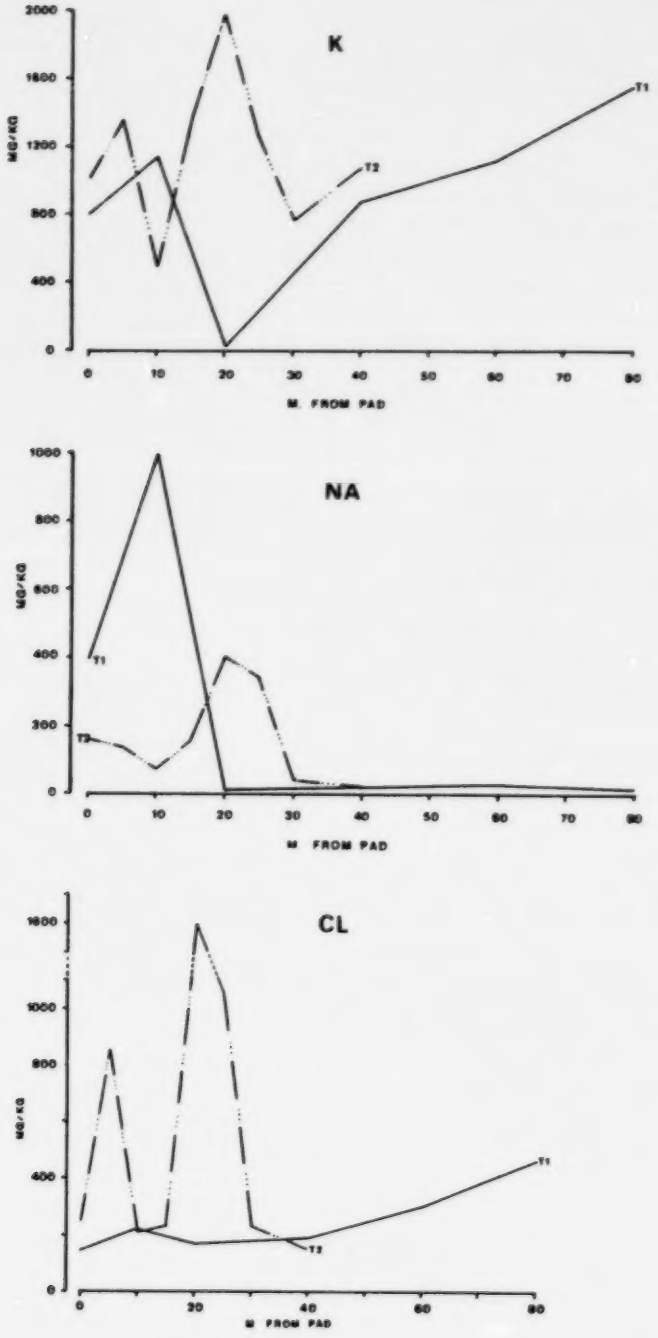


Fig. 7 Maps showing distribution of K, Na, and Cl in soil (0-10 cm depth) at the Peel H-71 wellsite, August 1980.

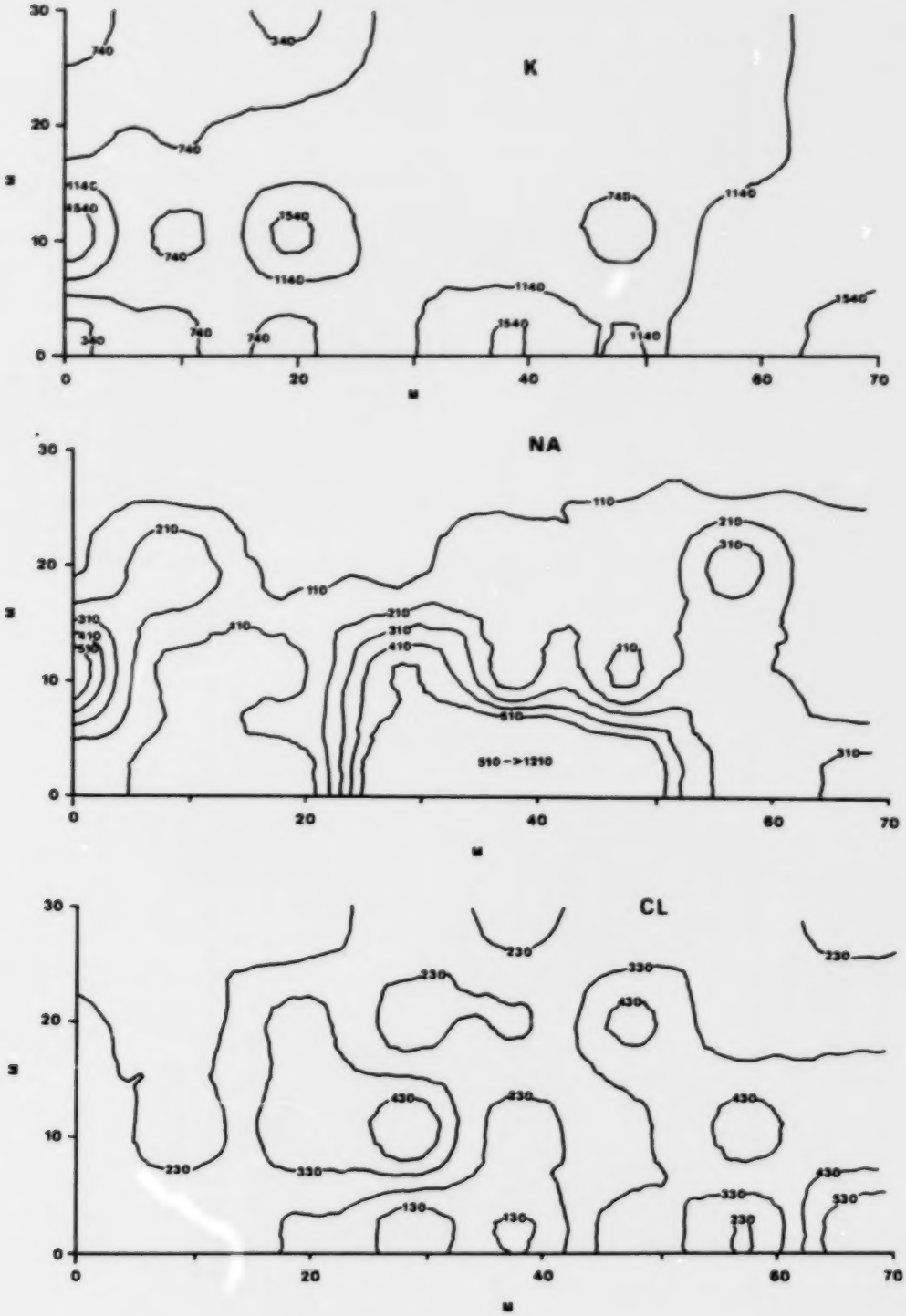


Fig. 8 Distribution maps of extractable K in surface soil (0-5 cm depth) at Parsons D-20, August 1978 and 1980.

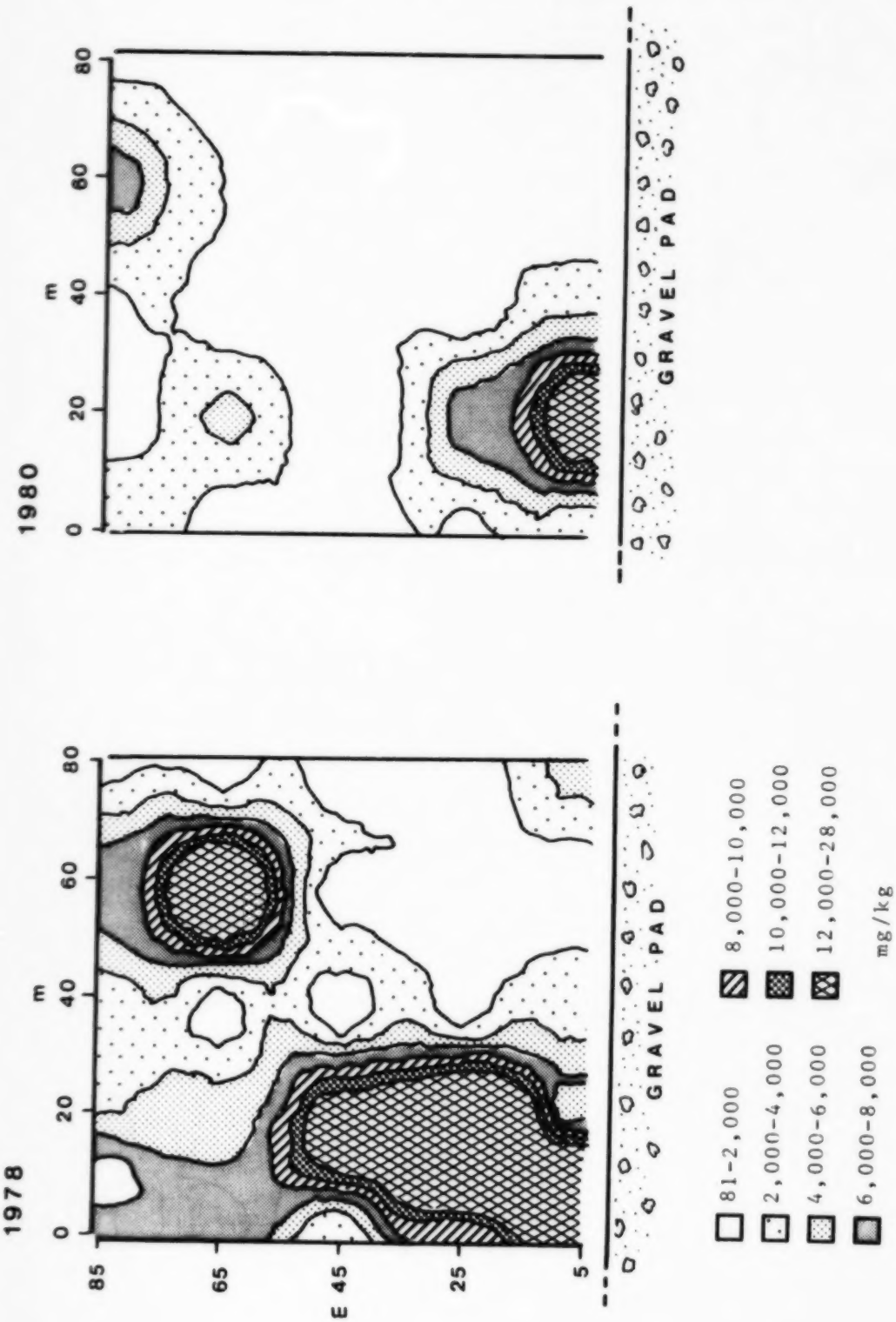


Fig. 9 Distribution maps of soil K (0-10 cm depth) in the 1978 spill at Parsons D-20, June 1979 and August 1980.

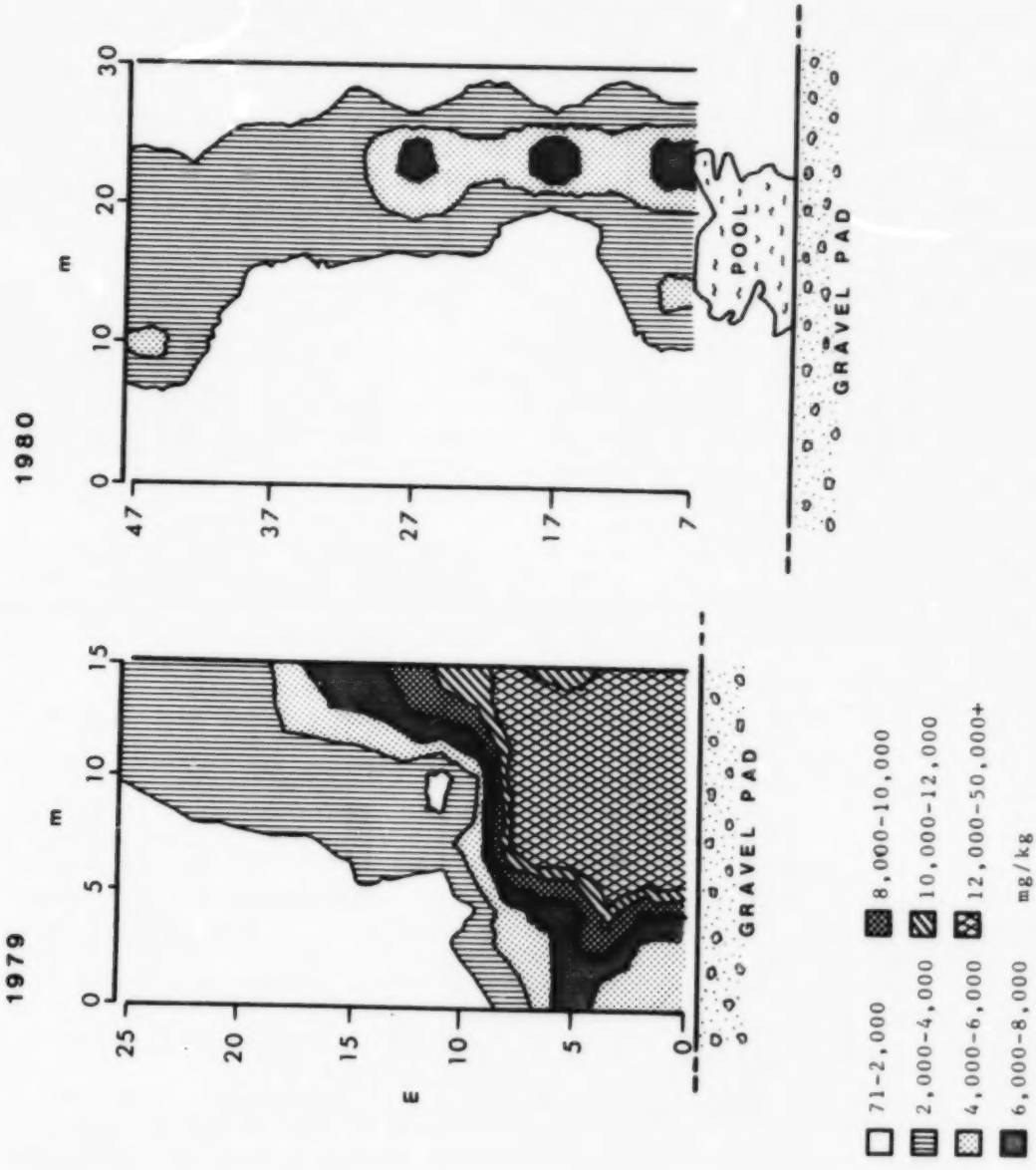
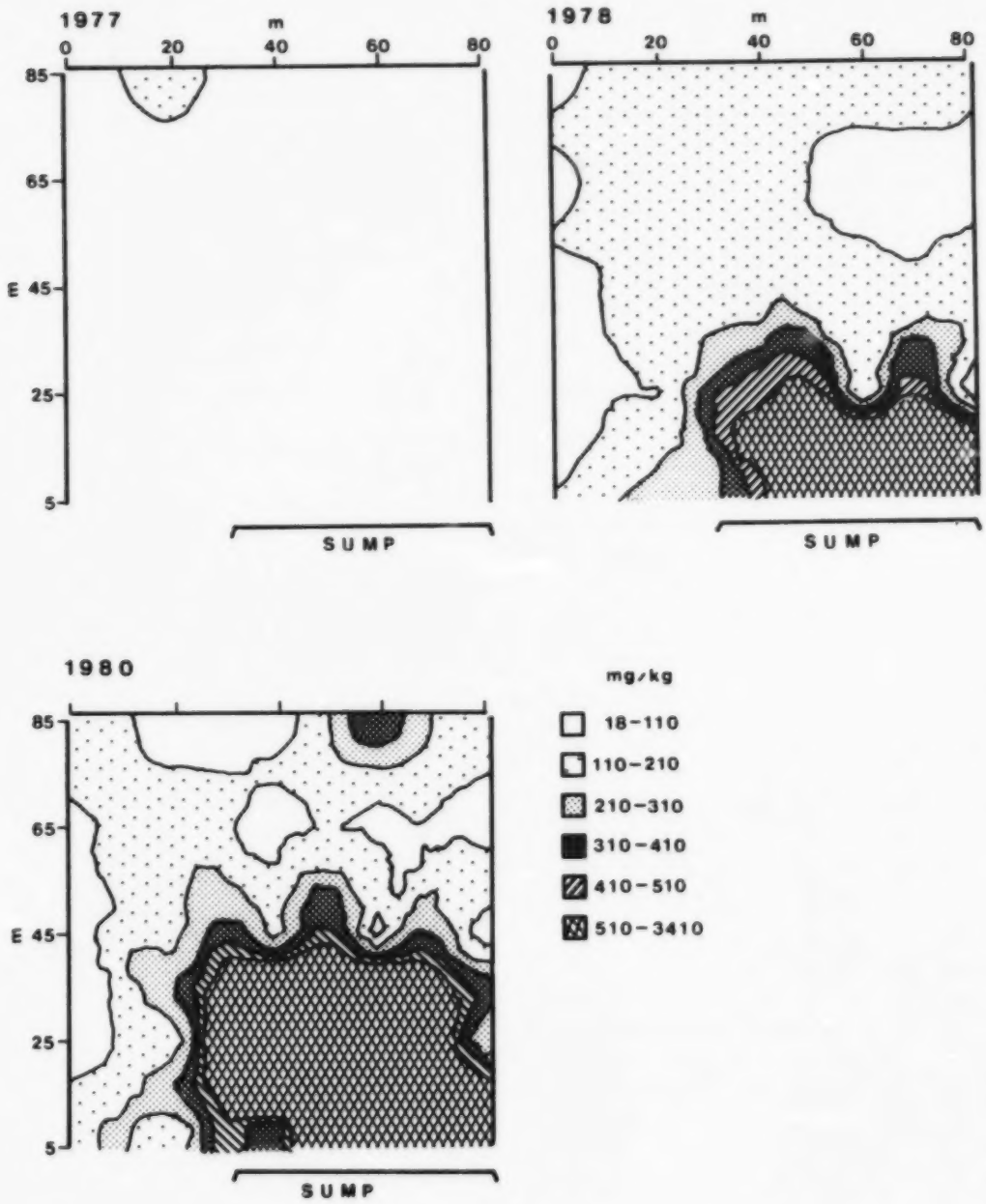


Fig. 10 Distribution maps of extractable Na in surface soil (0-5 cm depth) at Siku E-21, August 1977, 1978 and 1980.



surface (the highest extractable Na concentration in soil just above the frost-table was about one quarter of the maximum in the surface mud). There was no evidence that Na at these concentrations caused any structural deterioration of soils at either H-71 or E-21.

Soil contamination by Na was more severe and widespread at Parsons D-20. Surface concentrations measured in 1978 were about 500 to >989 mg/kg over 85% of the area sampled (Fig. 11) and Na levels in heavily contaminated soils were very high, ranging from a maximum of >3,000 mg/kg in the 1978 spill (Fig. 12) to >5,000 mg/kg in the 1977 spill (Fig. 11). Under these saline conditions (Richards 1969) dispersion of particles resulted in restricted drainage and structural changes in the surface clays, such as deflocculation and puddling (Edwards and Blauel 1975; McGeorge and Breazeale 1938). These changes rendered soils in the spill channels close to the sump highly susceptible to solifluction and mass wasting of the mineral material.

Levels of Cl in surface soils at H-71 (170-1,600 mg/kg) and E-21 (30-870 mg/kg) were similar, with slight contamination present at both sites. Elevated soil Cl at H-71 in 1979 resulted from leakage of sump fluids from the auxiliary sump along the west-draining channel (particularly noticeable on transect 2, Fig. 6). By 1980, however, downslope movement and spread of fluids through the organic surface layers resulted in a reduction of Cl in the drainage channel, but Cl at elevated concentrations occurred over a wider area (Fig. 7). At E-21, raised levels of soil Cl were directly associated with spillage of drilling mud. The greatest concentrations (270-870 mg/kg) were confined to the surface mud deposit (Fig. 13), although Cl contamination was more extensive than at H-71 with elevated post-spill levels at E-21 occurring over much of the sample grid (cf. Figs. 7 and 13). In general, though, Cl concentrations were low in soils at E-21 considering the large amounts of sump fluids spilled. This reflected the low initial chloride loading of the drilling mud (about 1% by weight).

Much of the large quantity of Cl added to the mud at D-20 passed into solution in the supernatant. Thus, when this supernatant leaked from the sump the result was widespread and severe contamination downslope with levels up to 57,000 mg/kg of Cl in the 1977 spill channel (Fig. 14) and >41,000 mg/kg in the 1978 spill (Fig. 15). Two to three years after initial spillage, soil chloride levels (measured on transects across the edge of the 1977 spill) were more closely correlated with levels of soil Na than K (Table 4), even though all of the Cl added to the D-20 drilling fluid was in the form of KCl. A complex of factors was probably responsible including chemical changes to the fluid wastes, and physical effects, such as differing rates of ionic movement through the soil and differences in fixation-adsorption rates of K and Na.

Vertical percolation of K, Na and Cl through the active layer occurred at D-20 and E-21 (not measured at H-71). At D-20, very high concentrations of these elements were found at the frost-table across the sample grids in 1978 and 1980 (max. values in mg/kg were 3,000 K, 439 Na and 3,600 Cl or about 175%, 600% and 610% greater than background respectively). In central regions of the 1977 spill channel the whole active layer was thoroughly permeated by sump fluids due to a combination of subsurface flow of saline fluids, vertical leaching of fluid, and migration of ion-rich water to the colder portions of the soil profile where it was trapped by the

Fig. 11 Distribution maps of extractable Na in surface soil (0-5 cm depth) at Parsons D-20, August 1978 and 1980.

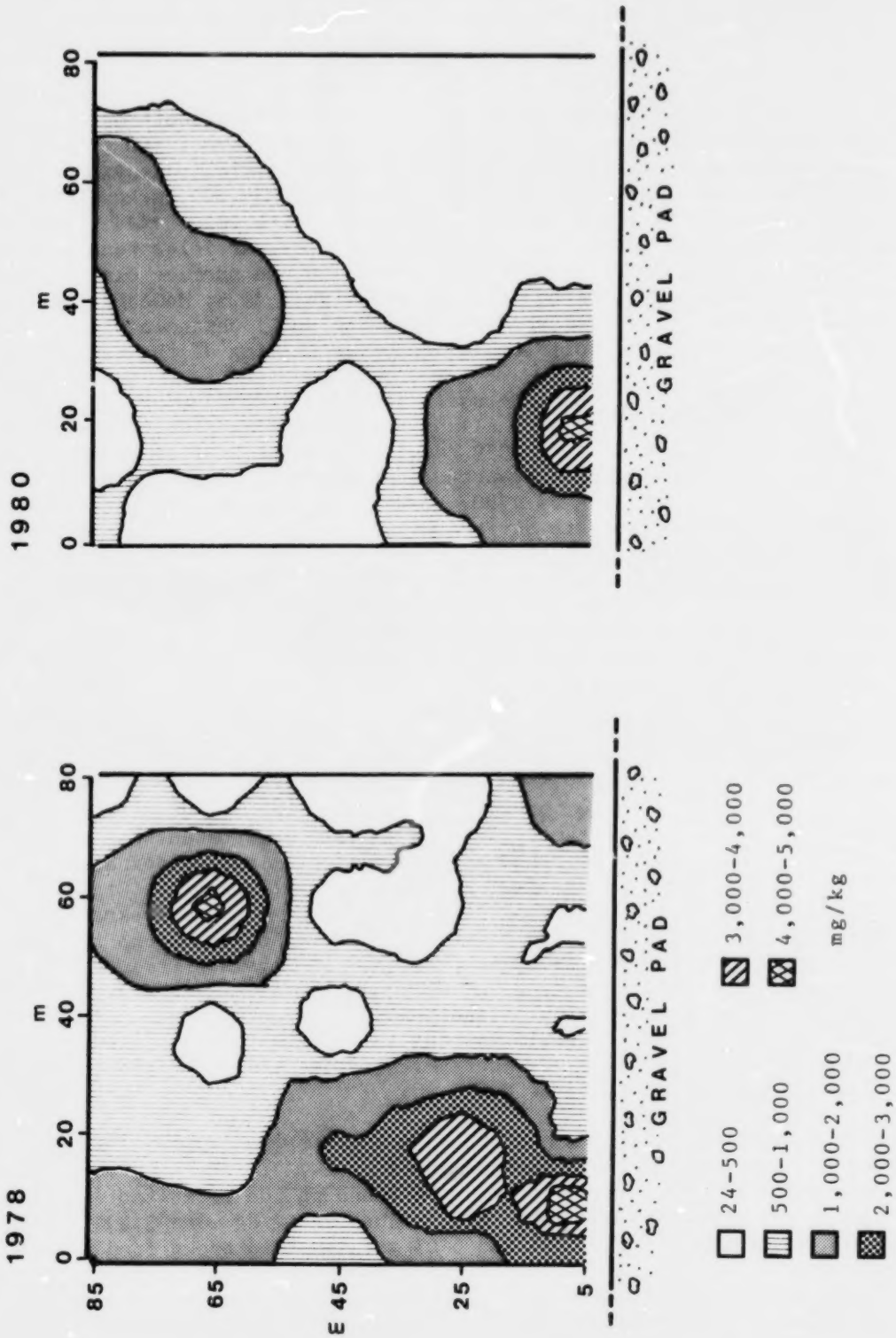


Fig. 12 Distribution maps of soil Na (0-10 cm depth) in the 1978 spill at Parsons D-20, June 1979 and August 1980.

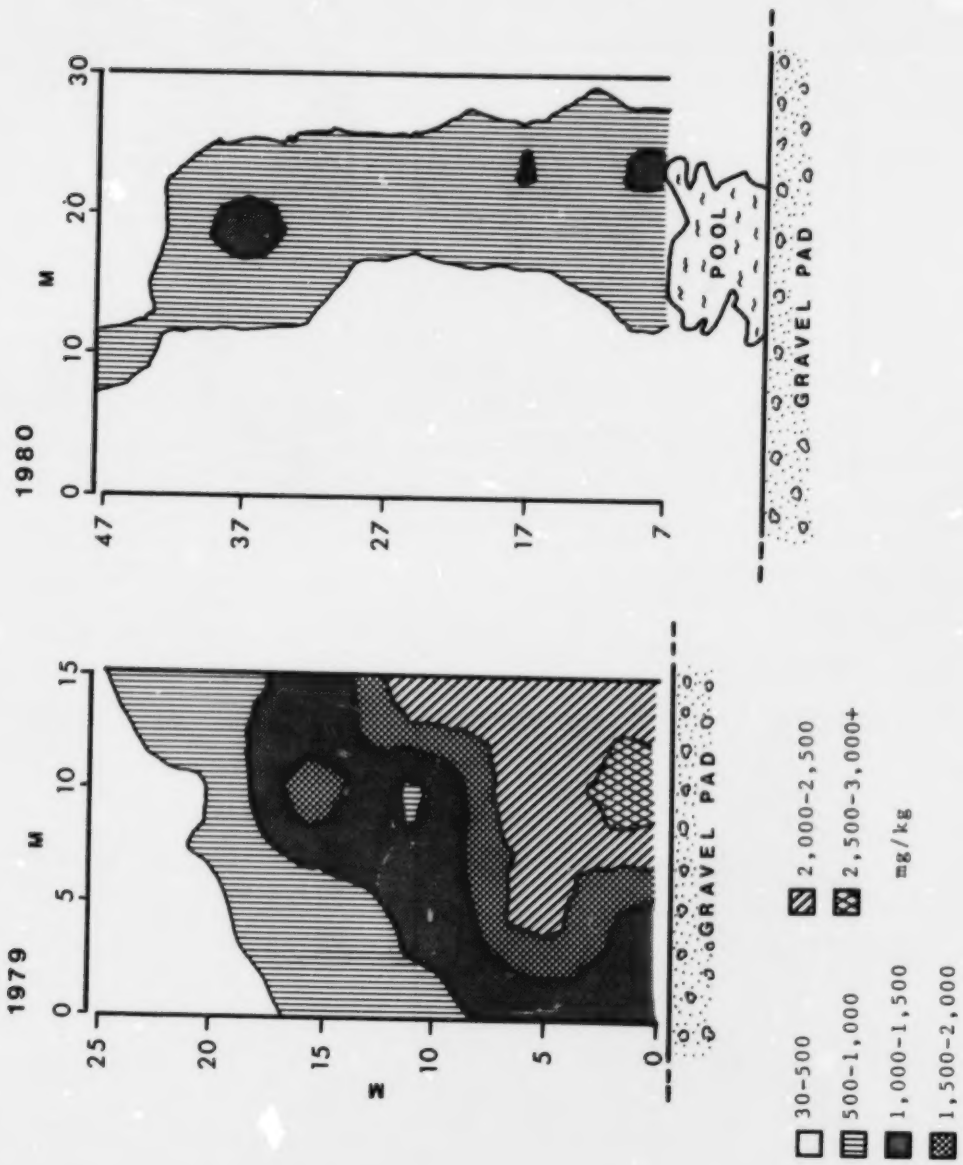


Fig. 13 Distribution maps of extractable Cl in surface soil (0-5 cm depth) at Siku E-21, August 1977, 1978 and 1980.

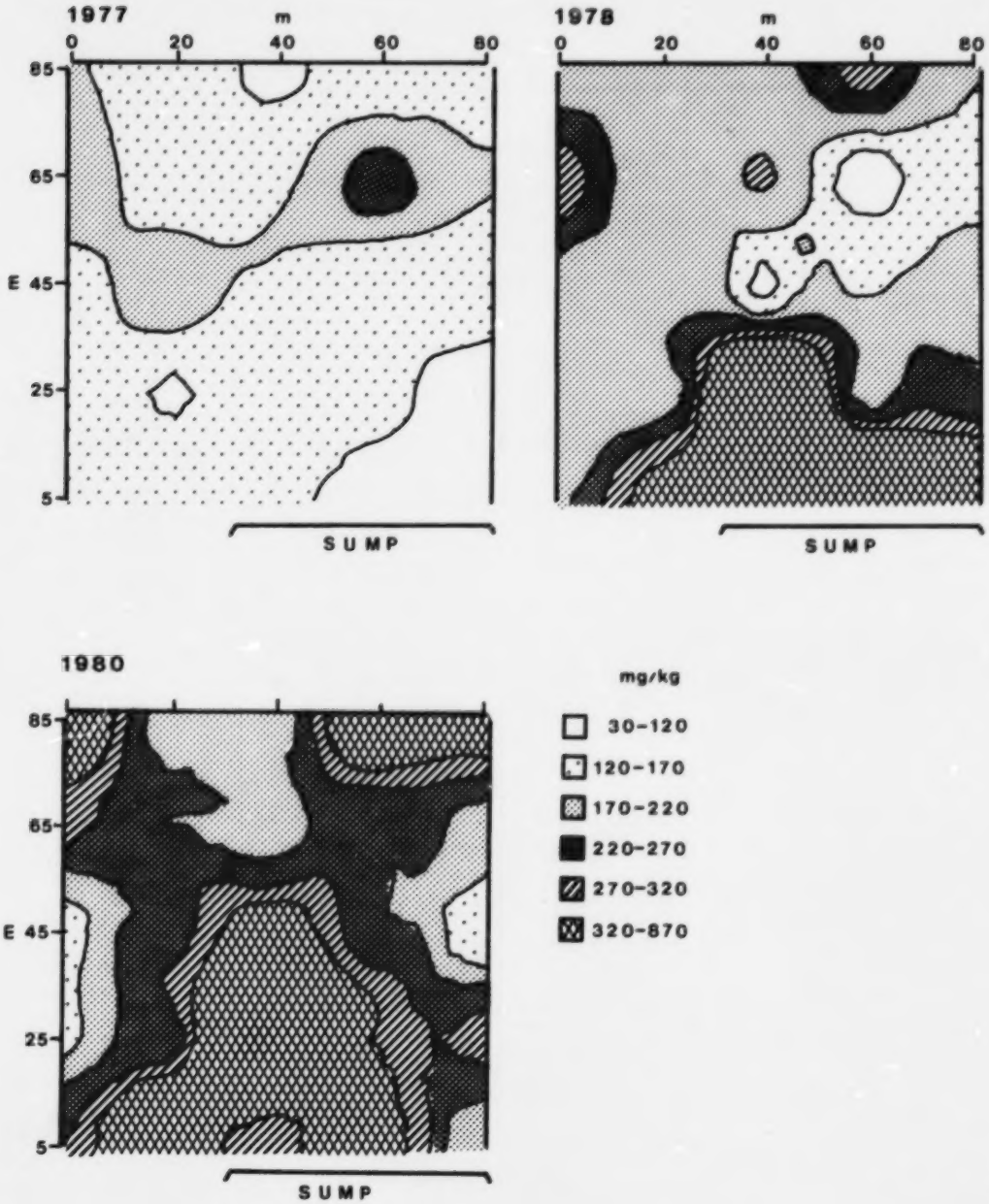


Fig. 14 Distribution maps of extractable Cl in surface soil (0-5 cm depth) at Parsons D-20, August 1978 and 1980.

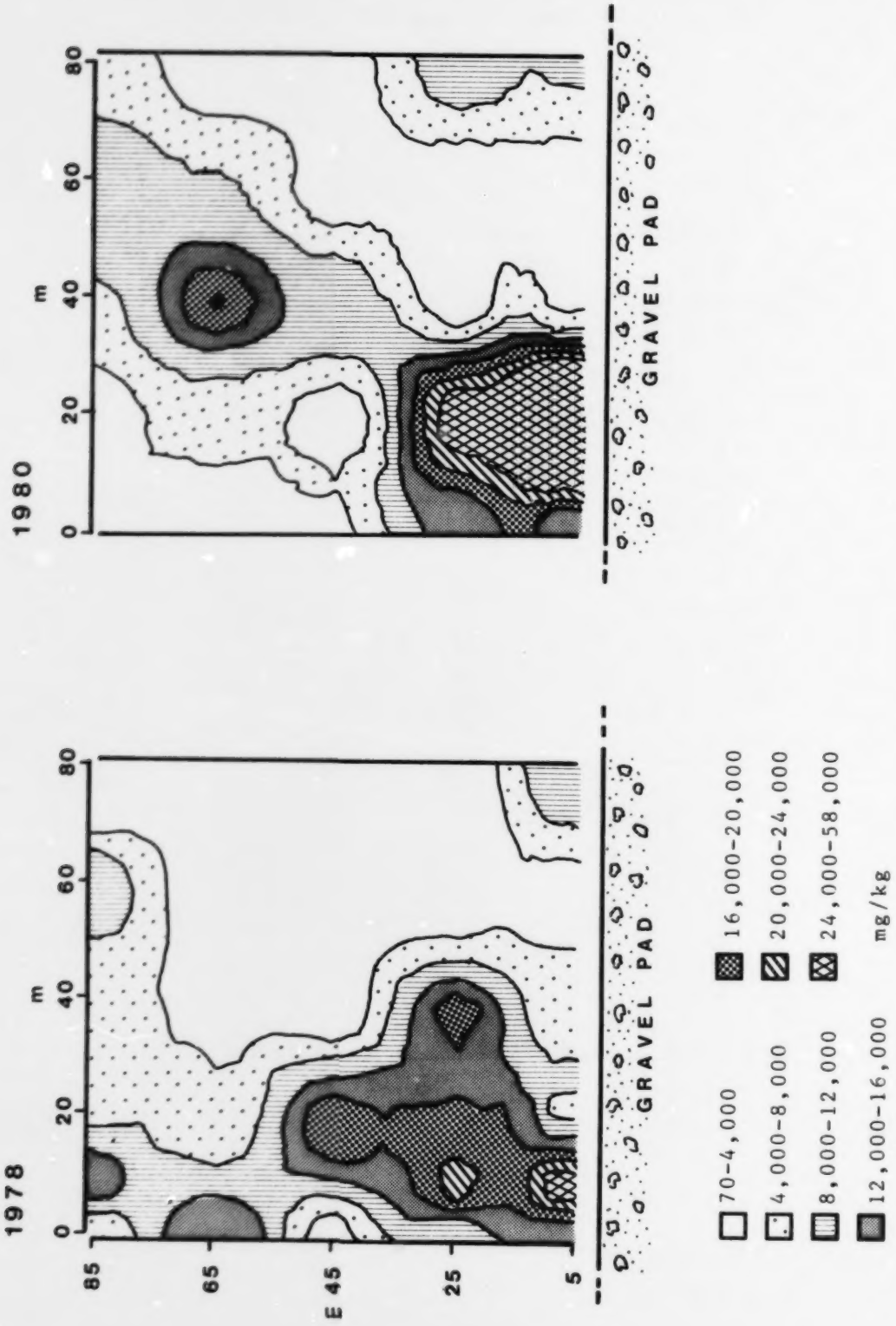


Fig. 15 Distribution maps of soil Cl (0-10 cm depth) in the 1978 spill at Parsons D-20, June 1979 and August 1980.

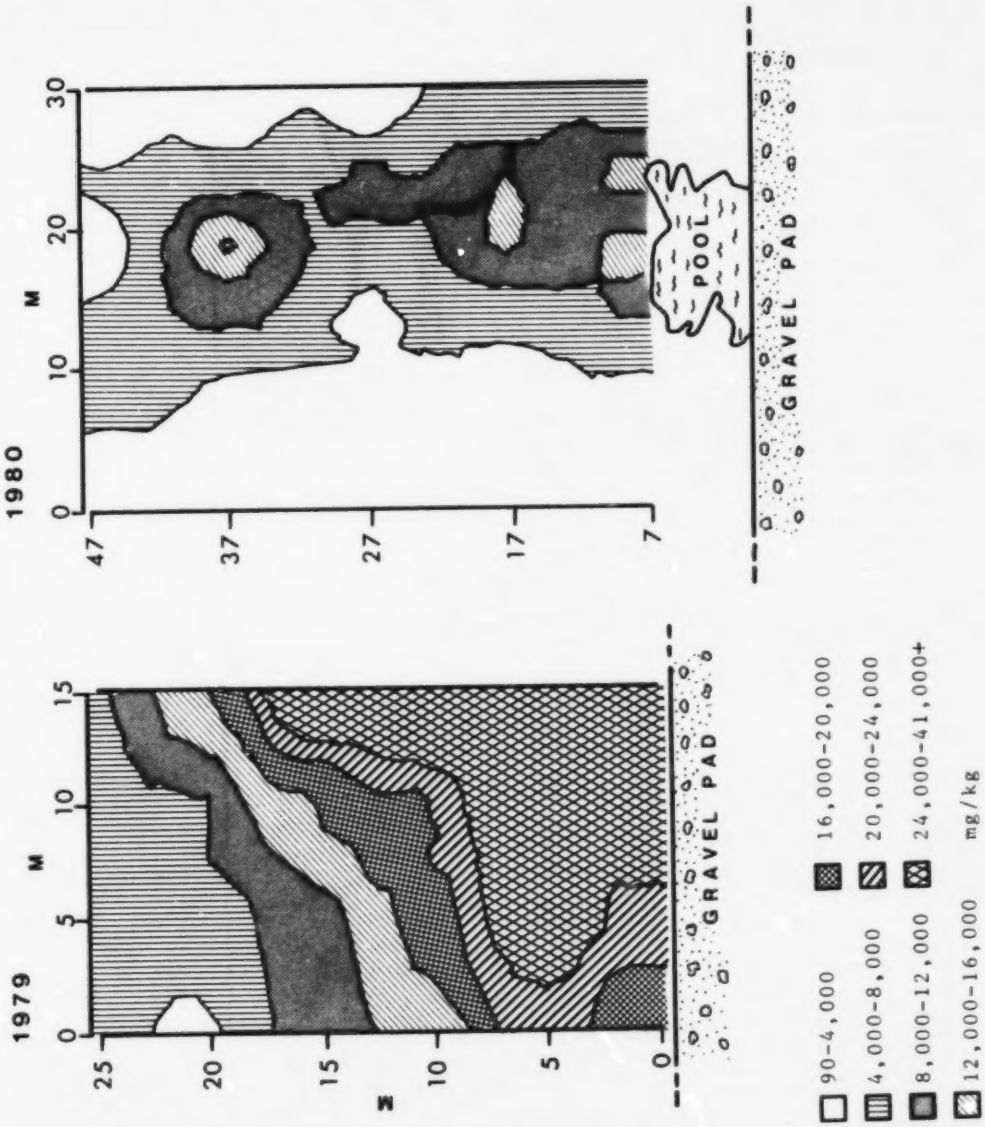


Table 4. Correlation between Cl and Na plus K concentrations (mg/kg) in surface soil along transects 1 and 2 (across the narrow boundary of the 1977 spill) at Parsons D-20, June 1979 and August 1980.

	Na		K	
	1979	1980	1979	1980
Correlation coefficient (r)	0.86	0.93	0.45	0.60
Significance (prob. level)	0.001	0.001	0.01	0.001

permafrost (described by Taylor 1965). At E-21, high subsurface levels of soil K, Na and Cl were restricted only to those areas buried under drilling mud. Maximum levels of these elements (in mg/kg) at the thaw interface, in the summer after fluid spillage, were 370 K, 235 Na and 276 Cl or about 690%, 440% and 290% greater than background respectively.

Lateral movement of soluble Na and Cl through soil on the gently sloping terrain at H-71 (Fig. 7) and E-21 (Figs. 10 and 13) led to some extension of the contaminated areas over time. At D-20, a similar lateral movement of K, Na and Cl was evident at the periphery of the 1977 spill where soil concentrations were generally higher at the spill-edge than at the more centrally located transect origins (Figs. 16 and 17). The distance travelled by soluble salts, however, was not great. Movement of soil salts parallel to contours was not prevalent at D-20 where initial spillage was from a point source, the downgrade slope was steep, and lateral extension was constrained by the topography. Relatively slight initial spread of sump fluids in 1977 correlates well with the narrow channel of injured plants observed after saltwater spills at other sloping sites (Edwards and Blauel 1975). Subsequent lateral extension of contaminated soils at D-20 occurred as sump fluids were moved downslope in a broad front by surface run-off and groundwater flow in spring 1978.

Some downslope movement of K, Na and Cl occurred at all three wellsites (Figs. 5, 7 to 15). Similar movement of these elements has been noted following spillage of saline fluids in Alberta (Edwards and Blauel 1975) and sump fluids in the high Arctic (Smith and James 1979). In all cases, migration was most rapid at the soil surface due to runoff. Other factors affecting the rate of ion movement included the solubility of compounds released from the sumps; soil composition; slope; and groundwater movement through the contaminated areas. At H-71 and E-21 downgrade movement was responsible for initial expansion of areas contaminated by Na and Cl particularly, but the distance travelled by these ions through the organic soils on shallow slopes was not great. Large-scale and long-distance (>200 m) movement of K, Na and Cl occurred at D-20 where slopes were steep and large volumes of salt-rich fluids escaped from the sump. However, mobile ions tend to migrate from upslope areas over time, thus, even heavy contamination of soils on the elevated topography at D-20 will be temporary, assuming no further release of sump fluids occurs. More permanent contamination may result from ponding of salt-rich groundwater in poorly-drained areas, e.g. frost-table depressions. At D-20, sump fluids accumulated in a flat, poorly-drained area of sphagnum peat at the base of a solifluction terrace immediately adjacent to Parsons Lake.

Sumps at all three wellsites were located in positions of relatively high topography at the top of slopes. The detrimental effects of this environmentally hazardous practice were illustrated at D-20 where factors favoring downslope movement of K, Na and Cl in toxic concentrations were maximized. At this site, the sump was located at the head of a 3->19° slope thus when saline supernatant leaked, it moved rapidly, under gravity, >200 m down to Parsons Lake following "natural" drainage channels. If leakage rates had been higher, slumping and mass wasting of the ice-rich soils, already subject to natural solifluction, would have occurred. As it was, a large quantity of fluids escaped from the sump and much damage to vegetation was done before remedial action could be taken. As a result, soluble salts in high concentrations were widely distributed through downslope soils two

Fig. 16 Concentrations of extractable Cl, K and Na in surface soil (mg/kg at 0-10 cm depth) on transect T1 at Parsons D-20, June 1979 and August 1980.

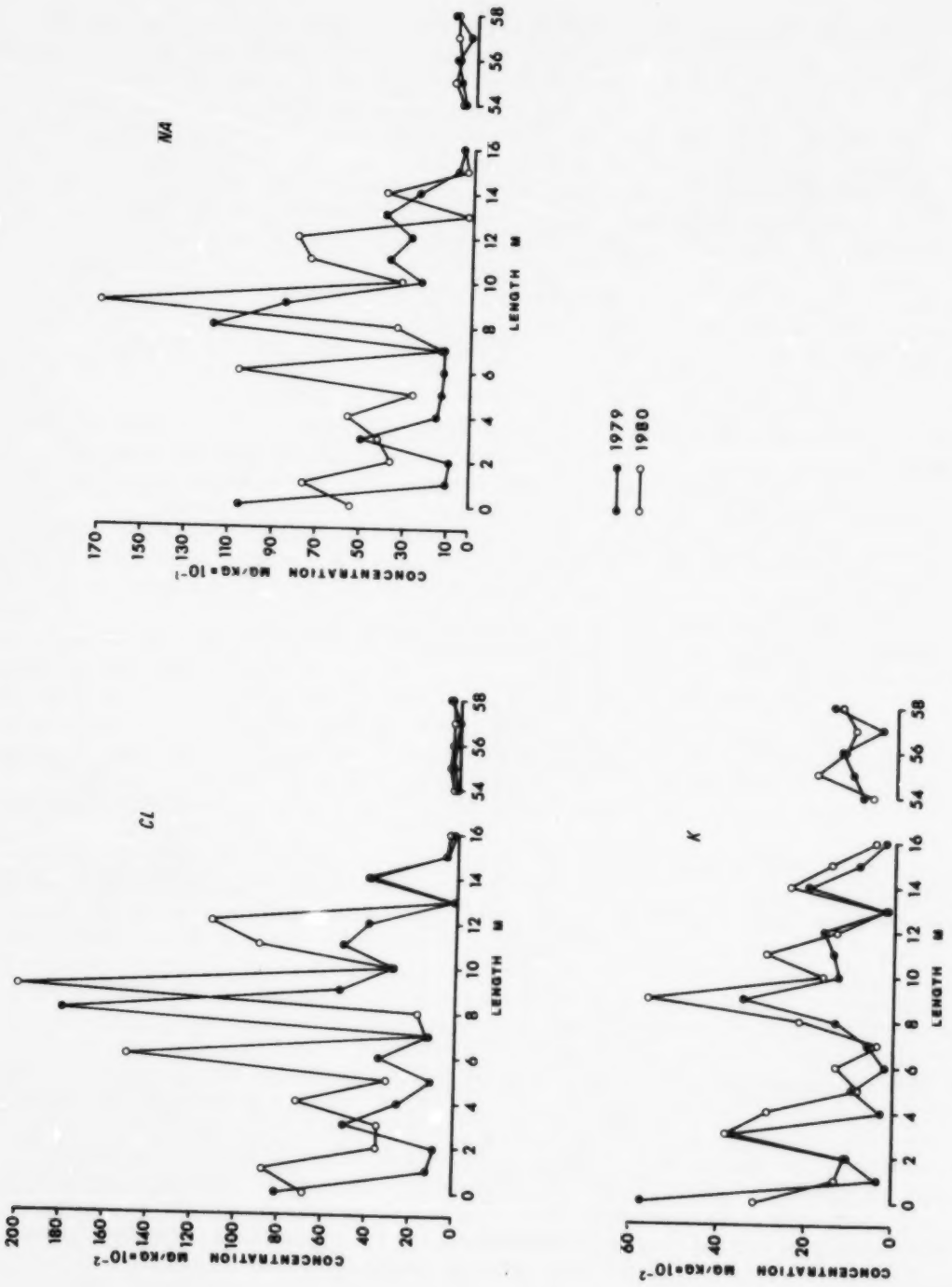
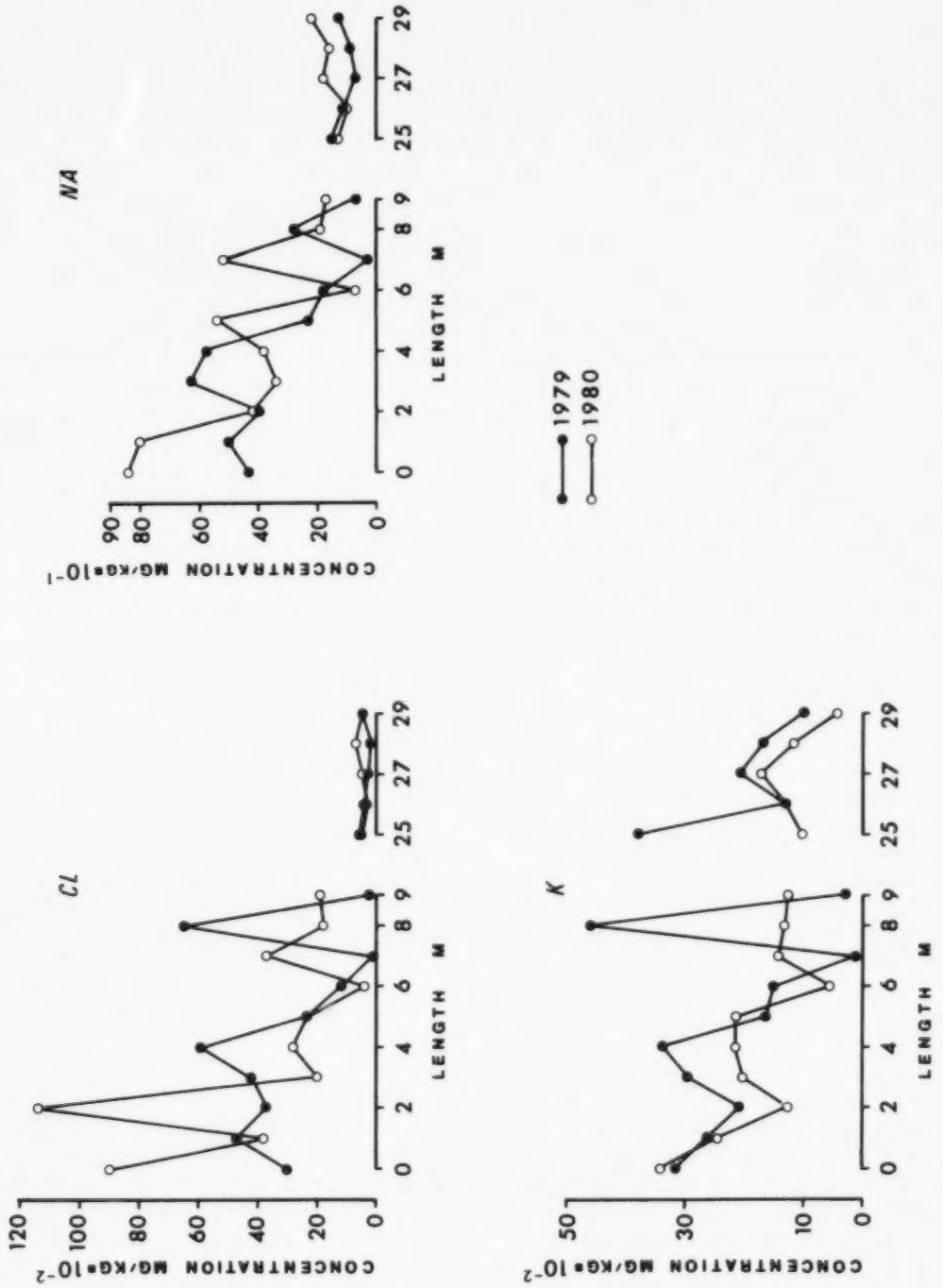


Fig. 17 Concentrations of extractable Cl, K and Na in surface soil (mg/kg at 0-10 cm depth) on transect T2 at Parsons D-20, June 1979 and August 1980.



years after the initial spill.

Effects of Sump Fluids on Vegetation

Visual observation and a number of quantitative analyses indicated widespread and severe damage to vegetation resulting from leakage of salt-rich fluids from the sump at Parsons D-20. Leakage of toxic fluids had its greatest impact on plants closest to the gravel pad over the sump. The mean species richness index (SRI) 5 m from the pad in 1978 was <50% of the SRI in undisturbed areas (Table 5). With the exception of Calamagrostis canadensis (artificially planted), all species in 1978, particularly lichens and mosses, occurred at lower frequencies near to the sump than in the undisturbed areas or at greater downslope distances (Table 5). In 1980, frequencies of most vascular plants within 5 m of the sump pad were lower than in 1978 (Table 5) showing the deleterious effects of prolonged exposure to saline sump fluids. The grass Arctagrostis arundinacea was an exception with the frequency in this same area increasing from 0% in 1978 to 80% in 1980.

Species frequencies and mean SRI between 25 m and 85 m from the sump pad in 1978 were similar to values in undisturbed areas (Table 5) conveying the misleading impression of vegetation existing in its natural state. In reality plants were disturbed by leakage of toxic sump fluids across the whole sample grid, especially in the 1977 spill channel where cover was reduced by more than 75%. Some plants (or parts of plants) survived, however, particularly on the mineral hummocks thus accounting for the apparent lack of change in species frequency in 1978. By 1980, even individuals rooted in the mineral hummocks were killed resulting in reduced frequencies and SRI values at 25-85 in from the pad (Table 5). Higher plants were the most affected by this long-term impact of sump fluid contamination, particularly Betula glandulosa, Carex sp., Empetrum hermaphroditum, Ledum decumbens, Petasites frigidus and Vaccinium Vitis-idaea. Decline in occurrence of these species was most marked in the 1977 spill channel at 65-85 m from the gravel pad (Table 5).

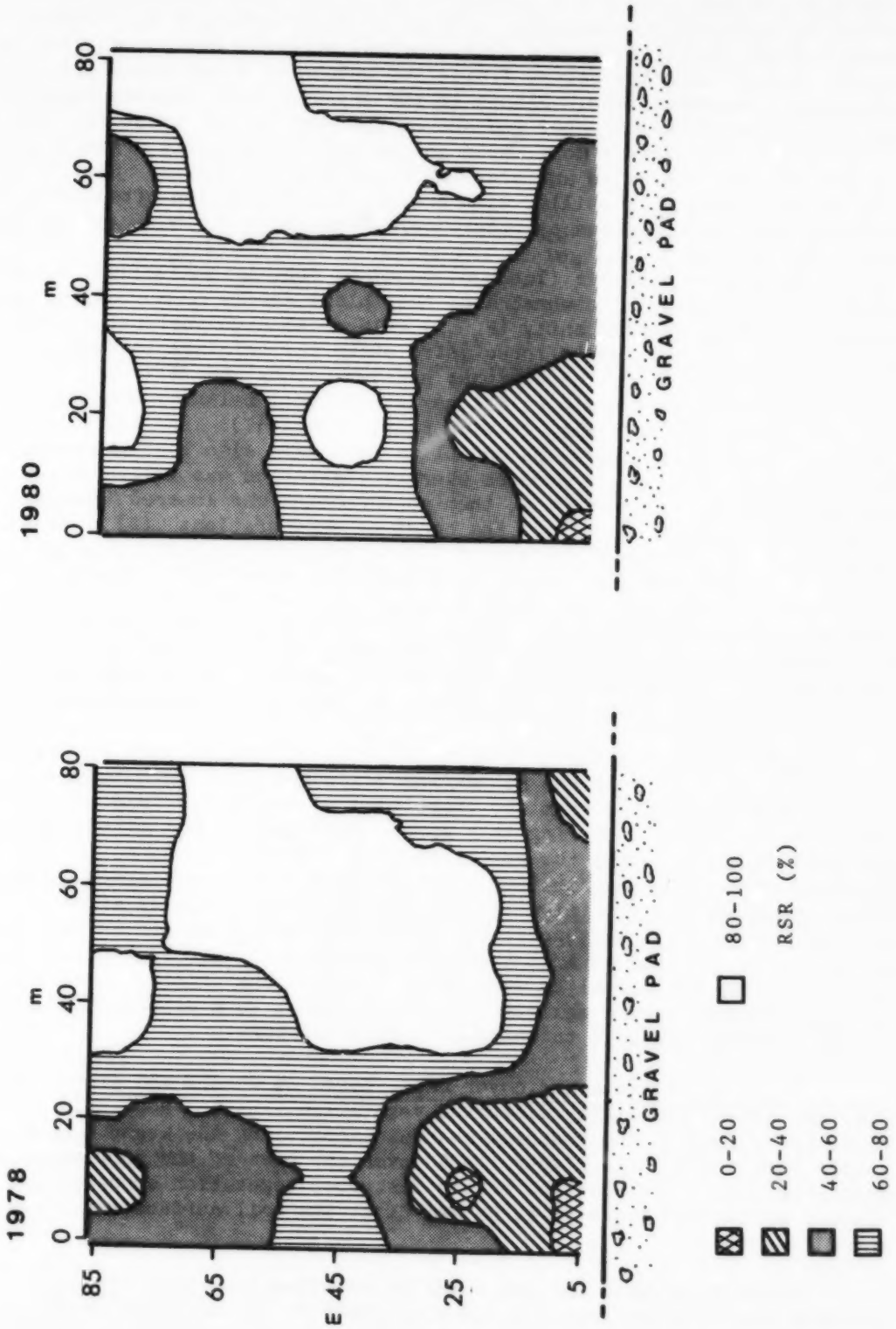
Relative species richness (RSR) maps (Fig. 18) showed that highly disturbed vegetation (RSR <40%) in 1978 was confined to the area adjacent to the gravel pad and the 1977 spill channel (left side of the 1978 map) at 5-30 m and 70-80 m downslope. This distribution corresponded closely with high soil levels of K, Na and Cl particularly at the surface (cf. Fig. 18 with Figs. 8, and 14). Destruction of higher plants resulted in a greater area of moderately disturbed vegetation (RSR 40-60%) in 1980 (Fig. 18) and a reduction in the area of least disturbed (RSR 80-100%) plants. Protracted exposure to toxic concentrations of K, Na and Cl in the leaked sump fluids was responsible for this change.

Vegetation damage at D-20 followed a pattern consistent with salt toxicity. The symptoms developed sequentially: 1) initial chlorosis; 2) leaf curling and tissue necrosis accompanied by reductions in vigour; 3) eventual defoliation and death. This sequence of plant damage was apparent along the periphery of the 1977 spill channel and observed by J. Campbell, Univ. of Alta. (personal communication) as fluids moved downslope from the sump. A similar progression of toxicity symptoms in broadleaved species has been observed following saline spills in Alberta (Edwards and Blauel 1975).

Table 5. Percentage frequency of plant species at Parsons D-20, August 1978; and August 1980 in brackets (UD - undisturbed area, -- sp. absent).

Species	Metres from gravel pad 5	25	45	65	85	UD
MOSSES						
Aulacomnium turgidum	25(--)	40(15)	40(40)	45(45)	40(30)	15
Dicranum elongatum	--(40)	85(40)	70(65)	80(35)	80(50)	65
Polytrichum commune	--(--)	5(--)	10(--)	--(--)	--(--)	--
Polytrichum strictum	--(--)	45(5)	20(20)	15(15)	50(15)	5
Sphagnum fallax	--(--)	--(--)	5(5)	--(--)	--(--)	--
Sphagnum russowii	10(--)	--(--)	15(--)	--(--)	--(--)	--
LICHENS						
Bryoria nitidula	--(5)	70(65)	60(60)	30(75)	25(85)	--
Cetraria laevigata	5(15)	35(25)	65(25)	50(15)	35(5)	40
Cetraria nivalis	35(40)	90(95)	90(100)	95(100)	100(90)	80
Cladina arbuscula	15(40)	90(100)	100(85)	100(100)	100(100)	85
Cladonia amaurocraea	--(15)	15(15)	45(45)	45(30)	25(60)	35
Cladonia coccifera	--(10)	--(20)	--(25)	--(30)	--(35)	--
Hypogymnia physodes	--(--)	--(--)	--(5)	5(--)	10(20)	--
Lichen sp.	10(5)	5(--)	--(--)	--(5)	10(20)	--
Peltigera apthosa	20(25)	70(55)	100(70)	80(95)	70(90)	45
Pertusaria dactylina	5(--)	20(--)	--(--)	--(--)	10(--)	10
HIGHER PLANTS						
Alnus crispa	--(--)	--(--)	--(--)	--(20)	--(15)	--
Arctagrostis arundinacea	--(80)	--(50)	--(70)	--(50)	10(50)	--
Arctostaphylos rubra	10(80)	35(20)	35(10)	5(15)	25(--)	15
Astralagus Richardsonii	--(10)	--(10)	5(--)	--(20)	--(--)	--
Betula glandulosa	15(--)	40(10)	45(40)	35(5)	80(30)	80
Calamagrostis lapponica	90(40)	25(--)	20(70)	10(--)	35(25)	40
Carex sp.	30(25)	75(45)	95(45)	100(50)	95(20)	80
Empetrum hermaphroditum	35(20)	65(60)	90(60)	90(40)	60(30)	75
Grass sp.	30(--)	--(--)	--(--)	--(--)	--(--)	--
Ledum decumbens	5(5)	55(55)	85(60)	75(40)	55(25)	80
Pedicularis labradorica	--(--)	10(--)	5(--)	--(--)	--(--)	--
Pedicularis lanata	--(5)	15(--)	30(--)	5(--)	--(--)	--
Petasites frigidus	45(35)	70(30)	65(40)	50(20)	35(25)	70
Poa lanata	20(--)	--(--)	--(--)	--(--)	--(--)	--
Pyrola grandiflora	--(--)	40(10)	30(--)	20(--)	10(--)	20
Pyrola secunda	--(--)	5(--)	30(--)	45(5)	15(--)	35
Rosa acicularis	--(--)	10(--)	--(--)	5(--)	5(5)	30
Rubus chamaemorus	--(5)	15(--)	--(--)	--(--)	15(--)	--
Rumex arcticus	--(--)	--(--)	5(--)	--(--)	--(--)	--
Salix glauca	--(--)	--(--)	--(--)	--(--)	--(--)	5
Saussurea angustifolia	40(10)	25(10)	5(5)	60(25)	35(35)	40
Stellaria longpipes	--(25)	20(5)	10(5)	5(15)	5(5)	5
Vaccinium Vitis-idaea	20(10)	75(60)	70(60)	75(45)	85(50)	75
MEAN SRI (%)	12(12)	29(21)	32(26)	29(23)	29(23)	26

Fig. 18 Maps of relative species richness (%) at Parsons D-20, August 1978 and 1980.



Death of vegetation in the heavily contaminated 1977 and 1978 spill channels was most likely due to salt shock (Repp 1958) whereby a rapid influx of salt-laden supernatant into a naturally low-salt environment subjected the plants to severe physiological stress. Damage resulted from direct contact with the saline fluids and uptake of K, Na and Cl in phytotoxic concentrations. Plants in the organic soils between hummocks were the first to be affected and showed the most severe symptoms. Salt infiltration was clearly most rapid in the highly permeable organics and slowest through the silts and clays of the mineral hummocks. Similar effects following salt spills, with hummock-top vegetation often escaping damage, have been reported by others, e.g. Edwards and Blauel (1975).

Regression analysis (Table 6) based on data gained in 1979 along the edges of the 1977 spill demonstrated that plant damage or mortality, in most cases, was still significantly ($P_{0.05}$) related to high residual levels of K, Na and Cl in the soil up to three years after the original leakage of sump fluids. There were some exceptions; however, along the 1977 spill boundary illustrative of the dynamic relations between soil salinity and vegetation response over time (cf. Fig. 19 with Figs. 16 and 17): (a) low plant cover in areas where levels of K, Na and Cl in soil were also low, this may have resulted from a two-stage process whereby vegetation was killed by the initial flush of saline fluids, then salt content was lowered (through dilution and migration) before the onset of regeneration; (b) high plant cover in areas where soil levels of K and Cl were also high, this perhaps resulted from movement of salt-rich fluids into previously undisturbed areas just prior to sampling (too short a lapse time for cover reduction), or salt levels in the soil (relatively high) were below phytotoxic concentrations. Fluctuating levels of soil salt with movements of ground and surface water are common along the edges of saline spills (Edwards and Blauel 1975) and contributed to the observed variability in plant-soil interactions.

Some vegetation damage attributable to leakage of sump fluids was apparent at H-71, but it was not extensive. Live plant cover generally increased with distance from the lease edge on transect 1 (Fig. 20) with the lowest cover (<30%) occurring in a narrow band from 0-10 m within the drainage channel west of the auxiliary sump. Cover reductions in this area resulted mainly from eradication or lowering of ericaceous shrub cover, with Ledum decumbens and Vaccinium Vitis-idaea being particularly affected (Table 6). On transect 2, plant cover was eradicated at the origin in the drainage channel (Fig. 20) due to both the toxic effect of fluids leaked from the auxiliary sump and burial by overburden. Beyond the origin, cover was variable ranging from a maximum at 5 m to <30% at 20 m with much of this variability attributable to changes in soil moisture.

Relative richness and cover maps, based on shrubs and ground cover species, showed the highly disturbed vegetation (RSR and RSC <40%) confined to a narrow band in the drainage channel paralleling the lease. These values were appreciably higher (>60%) over the rest of the 1980 sampling grid (Fig. 21). Distribution of the disturbed vegetation corresponded closely with high levels of K, Na and Cl at the soil surface (cf. Figs. 7 and 21).

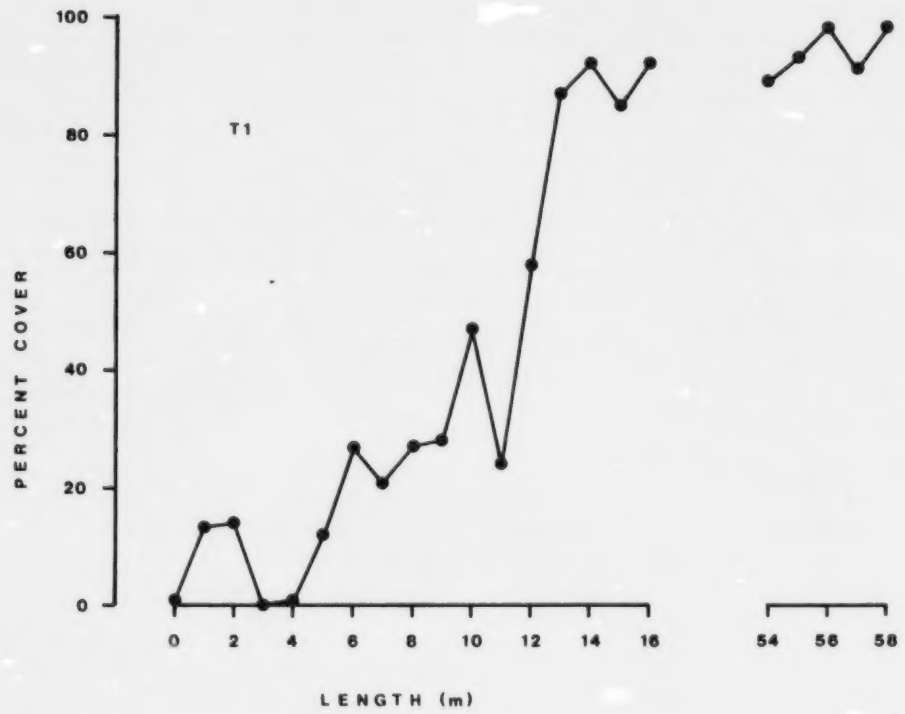
Chemical effects on tree cover at H-71 (mainly Picea mariana) occurred over a wider area (ca. 20 m adjacent to the drainage channel). Toxicity symptoms were consistent with salt stress described for this

Table 6. Simple and multiple regression analyses of % live plant cover (Y) and concentrations of K, Na and Cl (mg/kg) in surface soil along T1 and T2 at Parsons D-20, June 1979.

Simple regression (Y = a + bx)			
Independent (x)	Na	Cl	K
Intercept (a)	77.074	71.164	69.989
Slope (b)	-0.074	-0.005	-0.008
S.E.	0.020	0.002	0.005
r-squared	0.281	0.207	0.079
Sig. (p level)	0.001	0.010	N.S.
Multiple regression (Y = a + b1x + b2x + b3x)			
Intercept (a)	75.322		
Independent var. (x)	Na (b1)	Cl (b2)	K (b3)
Slope	-0.084	-0.0003	-0.002
S.E.	0.047	0.003	0.005
r-squared	0.284		
Sig. (p level)	0.050		

S.E. -- standard error
N.S. -- not significant

Fig. 19 Percent live plant cover on transects T1 and T2 at Parsons D-20, June 1979.



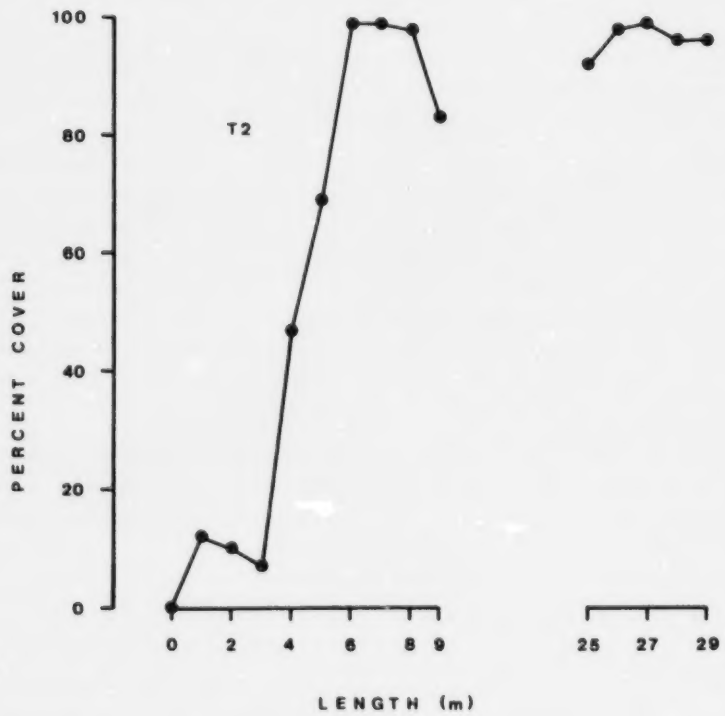


Fig. 20 Relative plant cover (%) on transects T1 and T2 at the Peel H-71 wellsite, July 1979.

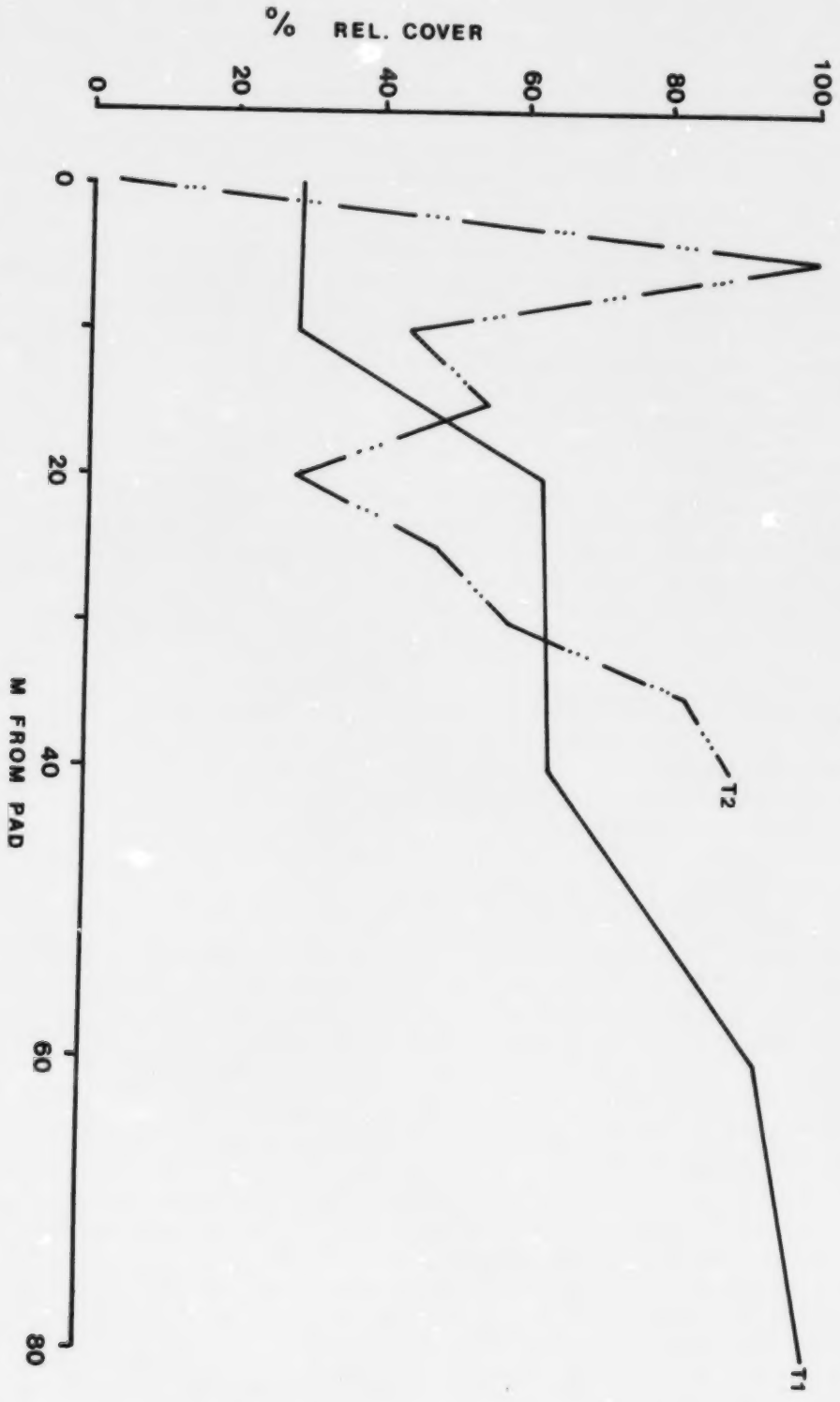
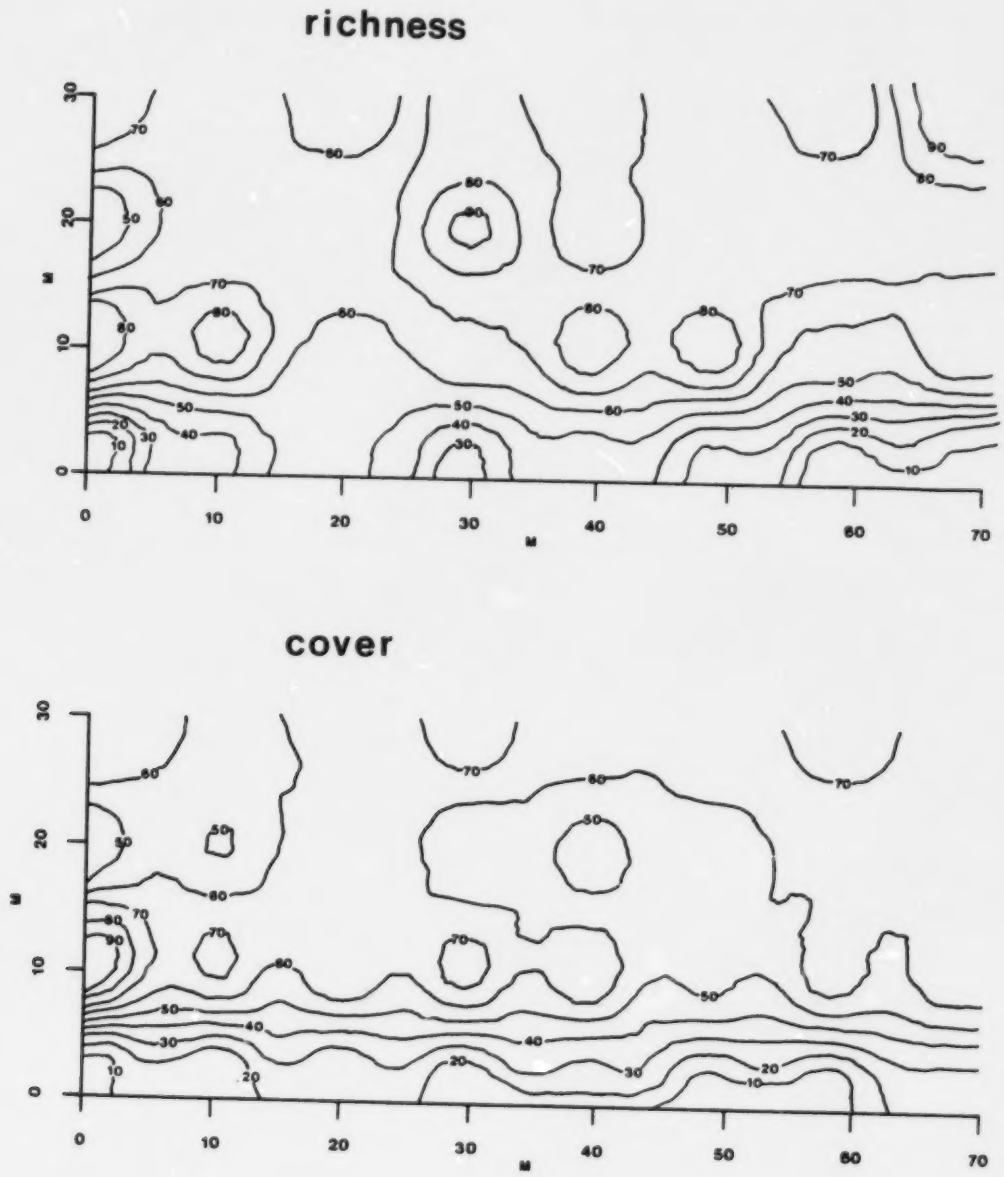


Fig. 21 Maps showing relative species richness (%) and cover (%) at the Peel H-71 wellsite, August 1980.



species by Edwards and Blauel (1975) with chlorosis of current and one-year foliage (light pink and stunted); older needles were reddish-brown; and, in some cases, defoliation had occurred with death of the tree.

Residual levels of salt in the soil at H-71 were low compared to D-20 (cf. Fig. 7 with Figs. 8, 11 and 14) and appeared to have little effect on the growth of established vegetation. Chemical damage at H-71 was probably related solely to the initial release of chemicals in toxic concentrations from the auxiliary sump.

Total salts and associated osmotic phenomena were not measured at D-20 and H-71. It does seem likely, though, that high osmotic pressures were a cause of physiological stress to plants growing in salt-enriched soils. Vegetation responses to salinity are complex. Treshow (1970) has stated that the harmful effect is mainly an excessive increase in osmotic pressure which acts to reduce the rate at which plants absorb water. Levitt (1970), on the other hand, argues that salt stress is primarily a result of specific ion toxicity and that osmotic phenomena are secondary.

It is well known that chloride is highly toxic to plants (e.g. Treshow 1970) and much of the initial injury to vegetation attributed to salinity is actually caused by this ion and its rapid movement through soils (Edwards and Blauel 1975). In Alberta, exposure to soil Cl levels above 15,000 mg/kg resulted in extensive plant mortality (Edwards and Blauel 1975); Cl levels of this magnitude and higher occurred over sizeable downslope areas at D-20 in 1978 and 1980.

High concentrations of K over wide areas at D-20 and in the drainage channel west of the auxiliary sump at H-71 may have adversely affected vegetation by inducing deficiencies in Mg (Foy and Barber 1958; McColloch et al. 1957) and Mn (Reuther and Smith 1954) causing iron chlorosis (Walsh and Clarke 1942), and retarding absorption of Zn (Reuther and Smith 1954). Increased absorption of K by plants may also decrease absorption of Ca (Chapman 1966) thus causing Ca deficiency. Potassium itself was probably not directly toxic at the concentrations measured.

Sodium concentrations in the spill channels at D-20 were 40% of the total exchangeable ions measured and at these levels Na had a negative effect on plant growth by causing structural deterioration of the fine-textured soils (see Kelley 1951; Martin and Richards 1959; Reeve et al. 1954). If the exchange complex is more than 40% Na then nutritional disturbance of plants may occur (Thorne 1945) as Ca is removed from the root tissue (Kelley 1951; Chang and Dregne 1955). Few cases of direct Na toxicity have been documented (Hayward and Wadleigh 1949; Richards 1969).

Contact with very high concentrations of K, Na and Cl indiscriminately killed all plant species at D-20 and in the drainage channel at H-71. At lower levels the various elements of the vegetation showed differing susceptibilities. Graminoids such as Arctagrostis arundinacea and Calamagrostis canadensis appeared the least susceptible; lichens such as Cladina arbuscula and Cetraria laevigata were intermediate; and woody shurbs, such as Betula glandulosa, and mosses; e.g. Dicranum elongatum, were the most susceptible (high moss sensitivity to KCl-rich sump fluids has also been noted by Strosher et al. 1978). None of the species at D-20 or H-71 appeared truly "salt tolerant" (able to withstand high

cumulative levels of Na and Cl, Edwards and Blauel 1975).

In marked contrast to D-20 and H-71, very little vegetation damage attributable to salinity was apparent at E-21. Symptoms of salt toxicity, such as leaf chlorosis and necrosis, were not observed even in areas of elevated soil K, Na and Cl. Plant damage was more related to burial by drilling mud and the effect of this physical disturbance on the overall vegetation complex was not great.

Mean frequencies and SRI values in 1978 and 1980 showed no correlation with proximity to the sump and mirrored the 1977 pre-spill condition (Tables 7 and 8). Negative consequences of spillage on the vegetation were mainly confined to those sample grid coordinates in areas of heavy (>20 cm deep) mud deposit. Lichens at thse coordinates were virtually eradicated by 1978 (shortly after spillage) and were completely absent, along with the mosses, by August 1980 (Table 9). Changes in frequency of the higher plants were more complex. Regeneration of Ledum decumbens, Rubus chamaemorus and Vaccinium Vitis-idaea was rapid hence there was little change in the frequencies of these species between 1977 and 1980 (Table 9). Other species; e.g. Calamagrostis canadensis and Betula glandulosa, regenerated rapidly following spillage (no reduction in frequency occurred between 1977 and 1978) but declined by 1980 (Table 9) suggesting that the newly regenerated aerial parts of these plants were susceptible to chemical contamination as they grew through the mud. Not surprisingly, the vegetation changes (listed above) were less marked in areas covered by a thin (<10 cm deep) mud layer as shown in Table 9.

Maps of relative species richness (RSR) at E-21 (Fig. 22) before spillage (1977) and after (1978, 1980) showed the highly disturbed vegetation with a low RSR (<45%) confined to a small area which closely matched the zone of drilling mud deposit 15-45 m from the sump (cf. Figs. 3 and 22) similar reductions in species cover (Fig. 23) were evident in those areas buried under a thick layer of mud. The two points of lowest RSC (<22%) marked the position of the two most severely disturbed coordinates identified by the RSR data (cf. Figs. 22 and 23).

Burial kills vegetation by crushing the plants, depriving them of light and oxygen, and mechanically impeding shoot elongation. Usually these effects are temporary and buried areas are recolonized, especially by regrowth of aerial stems from underground parts (widely evident at E-21).

Recovery of disturbed vegetation

Regeneration of some species at Siku E-21 was apparent five months after spillage of sump fluids as indicated by little change in species frequencies between 1977 (before spillage) and after spillage in 1978, 1980 (Tables 7 and 8). Vegetation recovery at the more heavily disturbed Parsons D-20 was much slower. No signs of revegetation were apparent in any of the spill-affected areas until 1980, three years after the initial leakage of sump fluids. The rate of cover regeneration at D-20 varied according to substrate type and the degree of contamination by saline fluids. Organic soils with a high residual salt content revegetated very slowly; contaminated mineral soil, particularly hummocks which escaped the initial saline spill and retained some live plant cover, appeared to revegetate

Table 7. Percentage frequency of plant species downslope of the sump at Siku E-21 in August 1977 and 1978 (in square brackets).

Species	Metres from sump 5	25	45	65	85
			% Frequency		
MOSSES					
Aulacomnium turgidum	35[25]	30[30]	15[25]	5[--]	5[15]
Dicranum elongatum	95[85]	90[55]	65[50]	75[75]	80[85]
Polytrichum commune	--[20]	--[15]	--[65]	--[--]	--[20]
Polytrichum strictum	70[85]	75[60]	55[50]	40[55]	50[40]
Sphagnum fallax	10[20]	15[20]	45[50]	--[--]	15[15]
Sphagnum russowii	--[--]	10[20]	10[5]	--[--]	--[--]
LICHENS					
Bryoria nitidula	55[20]	50[20]	40[40]	50[50]	45[40]
Cetraria laevigata	95[70]	70[55]	45[35]	55[50]	25[30]
Cetraria nivalis	65[95]	75[60]	40[40]	45[75]	65[60]
Cladina arbuscula	100[95]	100[65]	60[65]	100[95]	100[100]
Cladonia amaurocraea	15[10]	20[10]	30[5]	20[35]	45[85]
Cladonia coccifera	--[--]	--[--]	--[5]	--[--]	--[25]
Dactylina arctica	--[5]	10[--]	5[5]	--[--]	--[--]
Hypogymnia physodes	--[--]	--[--]	--[--]	--[15]	--[--]
Lichen sp.	--[--]	5[--]	25[--]	10[--]	25[--]
Peltigera apthosa	15[20]	--[--]	--[5]	--[--]	--[5]
HIGHER PLANTS					
Alnus crispa	25[10]	--[--]	--[--]	--[--]	--[--]
Arctostaphylos rubra	55[60]	25[10]	10[--]	--[--]	--[--]
Betula glandulosa	60[50]	60[70]	80[60]	70[70]	55[65]
Calamagrostis lapponica	--[--]	20[20]	--[--]	--[--]	--[--]
Carex sp.	90[85]	25[30]	55[55]	40[75]	40[45]
Empetrum hermaphroditum	50[45]	35[40]	25[25]	30[15]	15[10]
Grass sp.	--[10]	--[--]	--[20]	15[20]	--[--]
Grass sp.	15[--]	--[--]	--[--]	--[--]	--[--]
Ledum decumbens	100[100]	90[80]	100[100]	90[100]	95[100]
Oxycoccus microcarpum	10[20]	--[40]	--[--]	--[--]	--[--]
Pedicularis labradorica	10[15]	--[15]	5[10]	--[--]	--[15]
Petasites frigidus	25[20]	--[--]	--[--]	--[--]	--[--]
Rubus chamaemorus	100[95]	100[100]	100[90]	75[70]	65[70]
Vaccinium Vitis-idaea	100[100]	100[100]	100[95]	85[100]	100[100]
MEAN SRI (%)	36[37]	30[30]	28[29]	25[29]	25[30]

SRI - species richness index
-- - species absent

Table 8. Percentage frequency of plant species downslope of the sump at Siku E-21 in August 1980.

Species	Metres from sump 5	25	45	65	85
			% Frequency		
MOSSES					
Aulacomnium turgidum	50	30	30	15	20
Dicranum elongatum	80	55	50	90	85
Polytrichum commune	20	10	35	15	20
Polytrichum strictum	60	55	55	60	50
Sphagnum fallax	20	20	50	--	20
Sphagnum russowii	--	15	--	--	--
LICHENS					
Bryoria nitidula	25	35	40	55	45
Cetraria laevigata	85	60	40	60	35
Cetraria nivalis	75	45	40	75	65
Cladina arbuscula	85	55	70	100	90
Cladonia amaurocraea	--	15	35	60	75
Cladonia coccifera	--	5	45	30	60
Dactylina arctica	--	5	--	--	--
Hypogymnia physodes	--	--	20	20	20
Lichen sp.	--	--	--	--	--
Peltigera apthosa	--	--	5	5	5
HIGHER PLANTS					
Alnus crispa	15	--	--	--	--
Arctostaphylos rubra	55	10	--	--	--
Betula glandulosa	65	60	65	65	60
Calamagrostis lapponica	15	--	--	--	--
Carex sp.	95	25	75	60	10
Empetrum hermaphroditum	40	55	40	25	5
Grass sp.	--	--	5	--	20
Grass sp.	--	--	--	--	--
Ledum decumbens	90	90	95	100	100
Oxycoccus microcarpum	20	10	--	--	--
Pedicularis labradorica	--	--	5	--	--
Petasites frigidus	20	--	--	--	--
Rubus chamaemorus	95	100	100	70	75
Vaccinium Vitis-idaea	100	90	75	95	100
MEAN SRI (%)	36	27	31	32	31

SRI - species richness index
-- - species absent

Table 9. Percentage frequency of plant species at coordinates affected by heavy (20 cm depth) and light (10 cm depth) drilling mud deposits at Siku E-21.

Species	Year and mud deposit type					
	77(H)	78(H)	80(H)	77(L)	78(L)	80(L)
MOSSES						
Aulacomnium turgidum	--	--	--	50	--	50
Dicranum elongatum	100	25	--	100	75	88
Polytrichum commune	--	13	--	--	--	--
Polytrichum strictum	63	38	--	75	63	50
Sphagnum russowii	--	25	--	--	--	--
LICHENS						
Bryoria nitidula	63	--	--	25	25	13
Cetraria laevigata	50	--	--	100	75	75
Cetraria nivalis	63	--	--	100	88	88
Cladina arbuscula	100	13	--	100	88	63
Cladonia amaurocraea	13	--	--	25	--	--
Dactylina arctica	13	--	--	--	--	--
Lichen sp.	13	--	--	--	--	--
Peltigera apthosa	--	--	--	38	50	--
HIGHER PLANTS						
Arctostaphylos rubra	--	--	--	38	25	38
Betula glandulosa	63	75	38	63	75	63
Calamagrostis lapponica	50	50	--	--	--	25
Carex sp.	--	13	13	100	100	100
Empetrum hermaphroditum	--	--	25	38	25	25
Grass sp.	--	--	--	13	--	--
Ledum decumbens	75	50	75	100	100	100
Petasites frigidus	--	--	--	50	50	50
Rubus chamaemorus	100	100	100	100	100	100
Vaccinium Vitis-idaea	100	100	75	100	100	100
DRILLING MUD	--	100	100	--	88	50

(H) -- heavy drilling mud deposit
(L) -- light drilling mud deposit

Fig. 22 Maps of relative species richness (RSR, %) at Siku E-21, August 1977, 1978 and 1980.

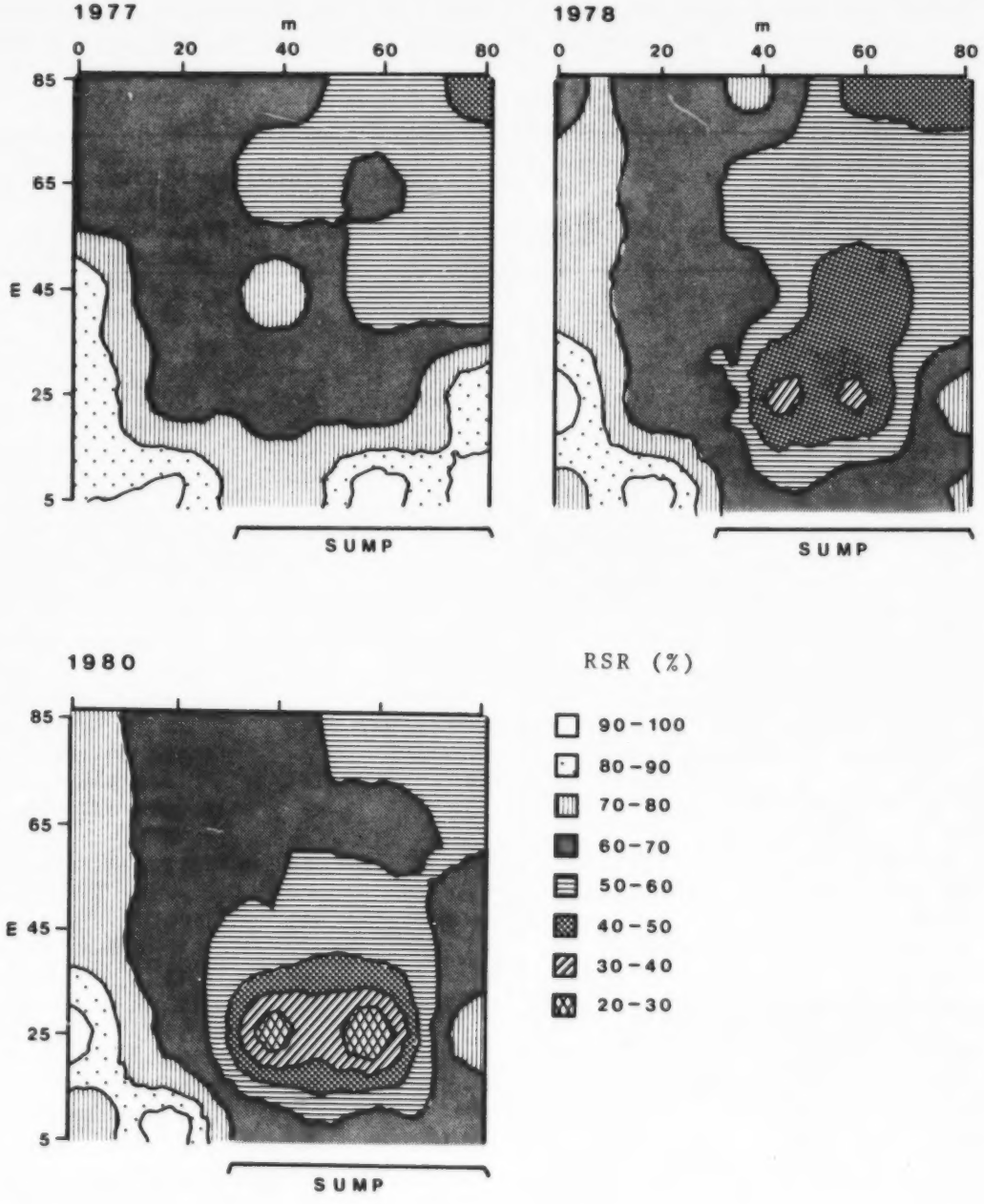
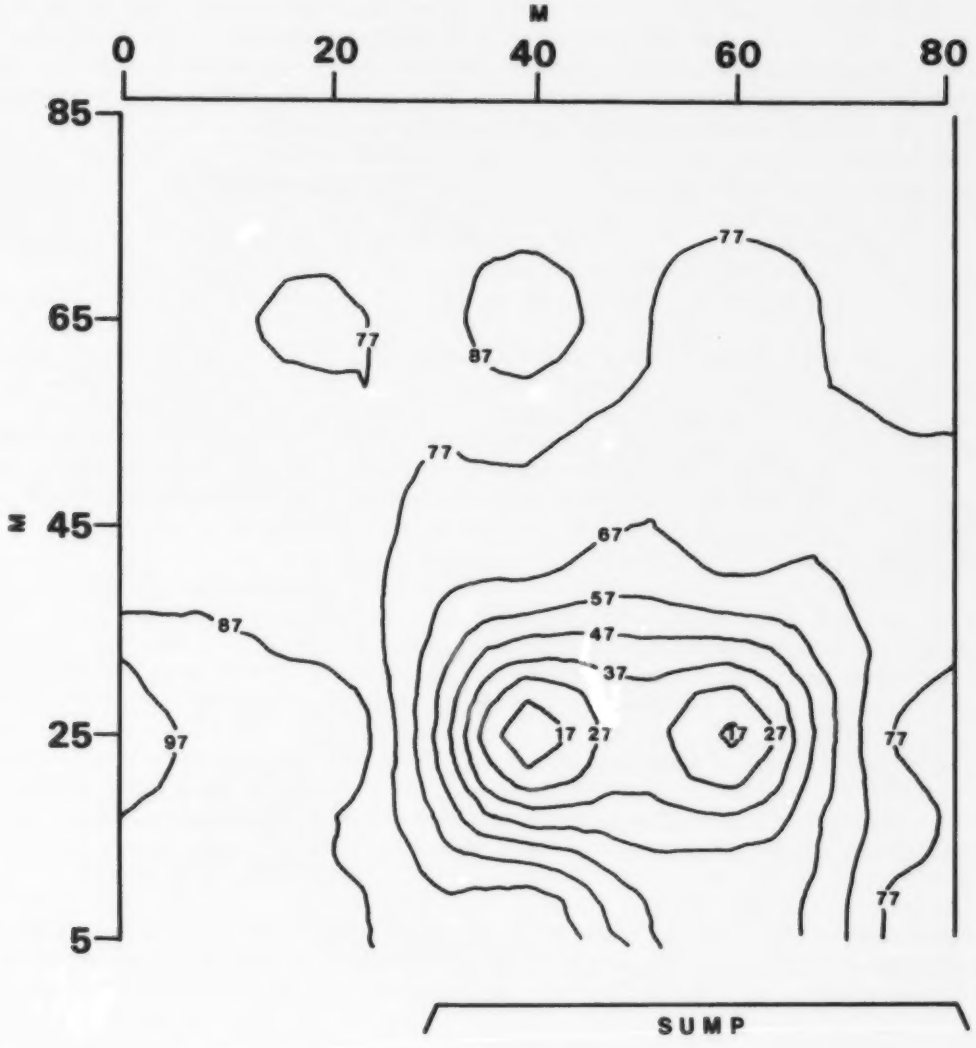


Fig. 23 Map of relative species cover (RSC, %) at Siku E-21, August 1980.



faster. In August 1980, recovery by the original vegetation was occurring on mineral soil contaminated in 1977, with native grasses making the most vigorous come-back (see Table 5, also Fig. 18 for increases in relative species richness at D-20 between 1978 and 1980). Recovery of vegetation in areas affected by sump fluid spillage was not apparent at H-71 two years after leakage (visual observation) and it appeared as if ongoing release of saline fluids, either from the auxiliary sump or contaminated fill was inhibiting colonization.

High salt levels in the soil inhibited regeneration of mosses at D-20 and thus moss recovery was non-existent in the main spill channels. Some moss regeneration was apparent on mineral soils where high initial salt loadings had been lowered by dilution and leaching. At E-21, Aulacomnium turgidum was observed growing on the surface drilling mud deposit, but other mosses were absent. Regeneration was through desiccation cracks in the mud deposit and the moss only colonized bare mud where moisture conditions permitted (usually at the base of polygon troughs). This is consistent with earlier observations. Babb and Bliss (1974) noted that mosses normally appear soon after disturbance at arctic sites given favorable microconditions and will multiply rapidly if protected from desiccation.

Lichens, except for a few isolated thalli of Cetraria laevigata and Cetraria arbuscula, were absent from the most heavily disturbed areas at E-21. At D-20, lichens were present in spill-affected areas but regeneration of killed thalli was not observed. High residual salt levels in the soil at D-20 seemed to inhibit lichen regrowth, although most species which survived the initial flush of saline fluids appeared healthy (Cetraria laevigata was an exception and continued to decline in contaminated areas in the years following spillage, see Tables 7 and 8).

Higher plants at E-21 mainly recovered by simultaneous regeneration through desiccation cracks in the surface mud deposit; there were no shifts in vascular plant dominance due to burial by drilling mud. The major recolonizers, Ledum decumbens, Rubus chamaemorus, Betula glandulosa, and Vaccinium Vitis-idaea, were also prominent in the undisturbed vegetation. All of these species were regenerating from buried vegetative structures.

Recolonization of spill-affected areas at D-20 was accomplished most efficiently by stoloniferous graminoids of which Arctagrostis arundinacea was the most prominent. Calamagrostis canadensis was also an important colonizer and predominant close to the sump where seed had been planted. Other notable recolonizers were Rubus chamaemorus and Petasites frigidus but these occurred at a much lower frequency than the grasses (see Tables 7 and 8).

There are a few species which can be favoured by disturbance. These "hemerophiles" (Kuc 1972) attain greatest vigour and ecological importance in disturbed rather than undisturbed, mature communities. Many species act as hemerophiles under appropriate conditions (Babb and Bliss 1974) but, in the Low Arctic, only a few have exceptional growth qualities in disturbed situations.

At D-20, both Arctagrostis arundinacea and Calamagrostis canadensis can be considered hemerophilic. These species (Calamagrostis canadensis was introduced as seed) achieved local dominance after leakage of sump fluids

and this represented a major ecological shift in that neither species is important in undisturbed Mackenzie Delta tundra. Similar observations have been made by others in the Low Arctic (Younkin 1973).

The success of Arctagrostis arundinacea and Calamagrostis canadensis as exploitative colonizers at D-20 was probably a function of: i) tolerance to saline conditions; ii) a large and viable seed source capable of germination under a wide range of temperature and moisture conditions; iii) overwintering ability; and iv) the ability of these species to send out a large number of creeping rhizomes which aid in the colonization of disturbed areas (Arctagrostis arundinacea will send out rhizomes with as many as 5-7 shoots/plant in its second year of growth, Younkin 1973). At D-20, Arctagrostis arundinacea was the most successful in colonizing disturbed areas, probably due to its ability to produce larger shoot and, particularly, root systems which are able to penetrate deeper into cold soils than those of Calamagrostis canadensis (Younkin 1973). Arctagrostis arundinacea is a truly arctic species, restricted to latitudes above 55°N and circumpolar in distribution.

RECOMMENDATIONS

The following recommendations are derived from our survey of Mackenzie Delta and N. Yukon wellsites and are based on the premise that containment of drilling wastes is necessary to prevent contamination of arctic terrain. The recommendations are not ranked in order of importance.

1. Sumps should continue to be used for containment of drilling wastes.

   Drilling fluids normally freeze in situ during a one winter period in the Low Arctic, hence, under most circumstances, sumps are an effective means of containment.

2. Sumps should not be located on elevated terrain on slopes or immediately adjacent to slopes. Where possible, sumps should be placed in enclosed natural depressions where excavation and sump construction can be minimized (a definite cost benefit).

   Conventional practice is to locate sumps at high points on the terrain close to or on slopes. The consequence, if sump failure or erosion of contaminated fill occurs, is chemical and physical disturbance of downslope terrain.

3. Selection of sump location should be based on a thorough onsite inspection, jointly by the drilling company and the government regulatory agency, during the snow-free period.

   The pre-drilling inspection will provide an information base from which the potential for waste spillage can be estimated and appropriate action taken immediately in the event of sump failure.

4. **Sumps should be infilled only after maximal amounts of their fluid contents are frozen (e.g. a minimum time of at least one winter).**

This is a modification of existing Land Use Regulations but is required on the recognition that in extreme instances of very high salt levels in the mud some fluid may remain indefinitely in a fluid or semi-fluid state. Under these circumstances maximal amounts of fluids should be frozen and infilling should be completed carefully to avoid upwelling of unfrozen fluid. In addition, excessive amounts of heavy infill materials should not be used.

5. **Construction of additional sumps during or after drilling operations should be avoided.**

Construction of additional sumps can result in excessive terrain disturbance, especially when the surface is unfrozen. Chemical contamination can also occur when fluids, contaminated fill, etc., are transferred to the auxiliary sump. Accurate calculation of final well depth, hence size of the sump needed to contain the drilling wastes, must be stressed by the regulatory agency together with adherence to existing regulations governing the use of sumps.

6. **Surface disposal of drilling wastes should be considered in areas where sump construction will cause severe terrain damage and providing the fluids are low in dissolved salts, especially KCl.**

We only recommend surface disposal of drilling wastes when these are guaranteed to be low (less than 10% by weight) in KCl. If surface disposal is used then the chemical composition of the wastes must be monitored regularly to preclude release of chemicals, particularly K, Na and Cl, in phytotoxic concentrations. The results of these analyses should be reported to the regulatory agency as soon as they are available. A contingency plan for alternate methods of waste disposal should accompany all applications for drilling without a sump.

7. **Summer drilling should be avoided whenever possible.**

Summer drilling exposes the sump to above-freezing temperatures for a number of months. As a result, considerable slumping and melting of ice bodies in the sump walls can occur. Terrain damage due to vehicle movement on unfrozen tundra is an additional problem when summer drilling is undertaken.

Logistical and economic considerations may necessitate summer drilling. In such circumstances, then sumps should always be lined with insulated plastic sheeting to minimize melting of the sump walls.

8. **Site rehabilitation measures should enhance natural revegetation processes or artificial revegetation should be completed.**

Creation of a roughed surface of fine fill overlying the coarser gravel

fill materials would enhance the rate of revegetation on unfilled sumps. Planting with grasses such as Arctagrostis arundinacea and Calamagrostis canadensis also assists in stabilizing erosion-prone surfaces and helps to ameliorate the harsh edaphic environment of bare areas thus allowing re-establishment of native species to proceed more rapidly. An artificial planting program was very successful at Parsons D-20.

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